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F. W. STECKER

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by

F. W. Stecker
Theoretical Studies Branch
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

ABSTRACT:

The production of ultrahigh energy photons, electrons and neutrinos as the decay products of pions produced in photomeson interactions between cosmic-ray nucleons and the blackbody microwave background is discussed in terms of the resultant energy spectra of these particles. Simple asymptotic formulas are given for calculating the ultrahigh energy photon spectrum predicted for the universal cosmic-ray hypothesis and the resulting spectra are compared with those obtained previously by numerical means using a different propagation equation for the photons. Approximate analytic solutions for the photon spectra are given in terms of simple power-law energy functions and slowly varying logarithmic functions. These can be used to estimate ultra-high energy photon fluxes for various astrophysical parameters. The generic relation between the various secondary components is then discussed in terms of their astrophysical implications which are summarized in the conclusion.

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The question of the origin of ultrahigh energy cosmic-rays evidenced by massive air-showers is still a matter of controversy. The older view of an extragalactic origin has recently been summarized by Brecher and Burbidge (1972). A more recent view of galactic origin has been argued for by Syrovatsky (1971) and by Stecker (1971), and we refer the reader to these references for the pertinent background discussion. The purpose of this paper is to discuss a possible test of the universal origin for ultrahigh energy cosmic-rays and also for the neutrino origin hypothesis of Berezinsky and Zatsepin (1969 a,b) . This test lies in a search for the ultrahigh energy photons which must be produced by photomeson interactions between "universal" ultrahigh energy cosmic-rays and the universal 2.7K microwave background radiation if both are present throughout the universe.

It was pointed out by Gould and Schréder (1966, 1967) and Jelly (1966) that photons with energy above 10^{14}eV will be seriously attenuated by pair-production interactions with the 2.7K background. However, recently Bonometto (1971) has pointed out that at the universe may be some two orders of magnitude more transparent to 10^{19}eV photons than had previously been estimated due to the development of an electromagnetic cascade process in the 2.7K radiation medium. In this cascade process, the initial photon interacts with a 2.7K background photon to produce an electron-positron pair, giving most of its energy to one of the electrons. This electron, in turn, Compton scatters with a 2.7K background photon to produce another photon with almost the same energy as the electron. Thus, the total effect of the two interactions is the same as if the original photon had been somewhat degraded in energy rather than completely absorbed. Thus, as Bonometto points out, this allows the transmission of photons of energy $E_\gamma \gtrsim 10^{19}$eV from effective distances of over $\sim 4 \times 10^{26}$cm (120Mpc). (Allcock and Wdowczyk (1972) considered this process in more detail). As a consequence, Wdowczyk, et al. (1971 a,b) have pointed out the possibility of observing photon initiated showers in good proportion to the total number of showers at energies $\sim 10^{19}$eV. It thus becomes important to estimate the intensity of these photons as Wdowczyk, et al. have done and to consider their generic relation to other possible components of ultrahigh energy cosmic radiation such as the neutrinos considered by Berezinsky and Zatsepin (1969a,b) whose mean-free-path is larger than the visible radius of the universe. In this paper, estimates are made of the ultrahigh energy photon, electron, and neutrino fluxes with assumptions which differ somewhat from those of Wdowczyk, et al. Simple asymptotic formulas are given for calculating the ultrahigh energy photon spectrum taking cascading into account and the results are compared with those of Wdowczyk, et al. (1971 a,b; 1972) and discussed. The approximate analytic solutions given here in terms of simple power-law energy functions and slowly varying logarithmic functions can be used to estimate fluxes of ultrahigh energy photons and other secondaries for various astrophysical parameters without resorting to numerical solutions.

The main source of ultrahigh energy photons is photomeson production interactions between ultrahigh energy cosmic-rays and blackbody photons of the 2.7K microwave background radiation i.e. interactions of the type $\gamma + p \rightarrow \pi^{0} + p$. This source may produce a detectable flux of 10^{19} - 10^{20} eV photons if both the 2.7K background and the ultrahigh energy cosmic rays are universal. To derive an approximate source function for the production of γ-rays in photomeson interactions with microwave blackbody photons, we assume all the photons to be at the average energy $\varepsilon_{o} \simeq 2.7\kappa T \simeq 6.4 \times 10^{-4}$ eV so that

$$n_{bb}(\varepsilon) = n_{bb}\,\delta(\varepsilon - \varepsilon_{o}),\; n_{bb} \simeq 400\mathrm{cm}^{-3} \tag{1}$$

The energy of the photon in the cosmic-ray proton rest system is

$$\varepsilon' = (E_p/M_p)\varepsilon_o(1-\cos\theta) \tag{2}$$

There is a large peak in the photomeson production cross section at $\varepsilon' \simeq 0.35 M_p$ due to the $\Delta(1238)$ resonance and since the cosmic-ray spectrum drops off rapidly with increasing energy, most of the pion production occurs at this resonance energy. Thus, from equation (2) we make the approximation

$$\sigma(\varepsilon') \simeq \sigma_o \delta \left[x - \frac{0.35 M_p^2}{\varepsilon_o E_p} \right] \equiv \sigma_o \delta (x - E_o / E_p) \qquad (3)$$

where

$$x \equiv 1 - \cos\theta, \quad E_o \equiv \frac{0.35 M_p^2}{\varepsilon_o} \simeq 4.8 \times 10^{20}\,\mathrm{eV}$$

and

$$\sigma_o \simeq 2 \times 10^{-28}\,\mathrm{cm}^2 .$$

Then the source function for γ-ray production may be written in the form

$$q(E_\gamma) = 4\pi \int_{E_\gamma + m_\pi^2/4E_\gamma}^{\infty} 2\, dE_\pi (E_\pi^2 - m_\pi^2)^{-\frac{1}{2}} n_{bb} \int_0^2 x\, dx \int_0^\infty dE_p I(E_p)\, \sigma(E_p, x)\, f(E_\pi | E_p) \qquad (4)$$

We assume all the pions to be produced at the average energy

$$\langle E_\pi \rangle = \frac{E_p}{2} \, \frac{m_\pi^2 + 2\varepsilon' M_p}{M_p^2 + 2\varepsilon' M_p} \qquad (5)$$

Using equation (4), equation (5) further reduces to

$$E_\pi \simeq \frac{E_p}{2} \frac{m_\pi^2 + 0.7M_p^2}{1.7M_p^2} \simeq E_p/5 \tag{6}$$

so that the distribution function is approximated by

$$f(E_\pi|E_p) \simeq \delta(E_\pi - E_p/5) \tag{7}$$

Further specifying the differential cosmic-ray proton spectrum by a power-law of the form $I(Ep) = K_pE_p^{-\Gamma}$ equation (4) reduces to

$$\begin{aligned} q(E_\gamma) &\simeq 8\pi n_{bb}\sigma_o K_p \int_{E_\gamma}^{\infty} dE_\pi/E_\pi \int_0^2 x\,dx \int_{(E_o/2)}^{\infty} dE_p\, E_p^{-\Gamma}\,\delta(x-E_o/E_p)\,\delta(E_\pi-E_p/5) \\ &\simeq 8\pi n_{bb}\sigma_o K_p(5E_o^{-\Gamma}) \int_0^{\mathrm{Max}\left[(E_o/5E_\gamma),2\right]} x^{(\Gamma-1)}\,dx \end{aligned} \tag{8}$$

The solution to equation (8) may then be written in the simple form

$$q(E_\gamma) = \begin{cases} Q_\gamma, & E_\gamma \leqslant E_1 \\ Q_\gamma(E_\gamma/E_1)^{-\Gamma}, & E_\gamma \geqslant E_1 \end{cases} \tag{9}$$

where $E_1 \equiv E_o/10 \simeq 4.8\times10^{19}$eV and

$$Q_\gamma = 8\pi n_{bb}\sigma_o K_p \frac{5^{(1-\Gamma)}}{\Gamma} E_1^{-\Gamma} = \text{const.} \qquad (10)$$

These photons travel, on the average, one mean free path $\lambda_{pp}(E_\gamma)$ before converting into an electron-positron pair with

$$1/\lambda_{pp}(E_\gamma) = (\pi\alpha^2/3\Lambda)(kT/m_e)^3(m_e^2/kTE_\gamma)\ \ell n\left[(0.117)(kTE_\gamma/m_e)\right] \qquad (11)$$

where $\Lambda \equiv \hbar/m_e c$ and $\alpha \simeq 1/137 = e^2/\hbar c$ (Gould and Schröder 1967)

The first-generation γ-rays reaching the earth from distances up to λ_{pp} then have a flux given by

$$I_1(E_\gamma) = q(E_\gamma)\lambda_{pp}(E_\gamma)/4\pi \qquad (12)$$

From equations (9), (11) and (12)

$$I_1(E_\gamma) = \frac{Q_\gamma}{4\pi}\ L\imath n(E_\gamma)\begin{cases}(E_\gamma/E_1) & , E_\gamma \leqslant E_1 \\ (E_\gamma/E_1)^{-(\Gamma-1)} & , E_\gamma \geqslant E_1\end{cases} \qquad (13)$$

where

$$\frac{Q_\gamma}{4\pi} = \frac{8\times10^{-25} K_p}{\Gamma(2.4\times10^{20})^\Gamma}\ \text{cm}^{-3}\text{s}^{-1}\text{sr}^{-1}\text{eV}^{-1} \qquad (14)$$

$$\eta(E_\gamma) = 4.34/(\log_{10} E_\gamma - 15.97) \tag{15}$$

and $L_1 = 1.0 \times 10^{25}$ cm.

As discussed previously, photons undergoing pair conversion interactions after traveling distances $\sim\lambda_{pp}$ or greater, give up most of their energy to one electron. The fraction of energy given off to the other electron is given by

$$\delta_{pp} \equiv \left\langle \frac{E_\gamma - E_e}{E_\gamma} \right\rangle \rightarrow \frac{\ell n\ 2 + 1/4}{\ell n(E_\gamma/\mathcal{E}) - 1} \tag{16}$$

where

$$\mathcal{E} \equiv m_e^2/2\varepsilon_o \simeq 2.08 \times 10^{14} \text{ eV}$$

If the intergalactic magnetic field is weak enough so the Compton interactions with the microwave radiation dominate over synchrotron radiation as an energy loss mechanism, as discussed by Wdowczyk, et al. (1972) in the Klein-Nishina high-energy limit ($E_\gamma >> \mathcal{E}$), the electron will transfer most of its energy to a microwave photon in a Compton interaction, converting it into a secondary ultrahigh energy photon. The difference in energy between the incoming electron and outgoing photon is

$$\delta_c \equiv \left\langle \frac{E_e - E_\gamma}{E_e} \right\rangle \rightarrow \frac{4/3}{\ell n(E_e/\mathcal{E}) + 1/2} \tag{17}$$

In this manner cascade secondary photons can be generated producing a total flux greater than $I_1(E_\gamma)$. Wdowczyk, et al. (1971a,b;1972) have made numerical calculations of the total flux, $I_\Sigma(E_\gamma)$ generated in the cascade. Here, we use a different approach to derive a simple approximate solution for $I_\Sigma(E_\gamma)$. The key to our approach lies in the fact that the total effect of the two-stage pair production-Compton process is to replace a photon of energy E by one of energy $E_\gamma(1-\delta_{pp})(1-\delta_c)$. Under the conditions $\delta_{pp} \ll 1$ and $\delta_c \ll 1$, the two stage process can be treated as a continuous energy-loss at a rate

$$u(E_\gamma) \equiv dE_\gamma/dt \tag{18}$$

and I_Σ can be approximated by a solution to the diffusion equation

$$\frac{\partial}{\partial E_\gamma}\left[\frac{4\pi}{c}\, uI_\Sigma\right] = f_\gamma q(E_\gamma) \tag{19}$$

with the solution

$$I_\Sigma(E_\gamma) = \frac{c}{4\pi}\frac{f_\gamma}{|u(E_\gamma)|}\int_{E_\gamma}^{\infty} dE_\gamma' \; q(E_\gamma') \tag{20}$$

where, in equations (19) and (20), f_γ represents the mean portion of primary photons which are at any given time in the form of secondary photons rather than secondary electrons. This fraction is derived from the ratio of lifetime of photons against pair-production τ_{pp} to that of electrons against Compton scattering τ_c where, for $E_e=E_\gamma \gg \mathcal{E}$

$$(\tau_{pp}/\tau_c)_{E_e=E_\gamma=E} = (\sigma_c/\sigma_{pp}) \rightarrow \frac{1}{2}\,\frac{\ln(E/\mathcal{E})+1/2}{\ln(E/\mathcal{E})-1} \qquad (21)$$

Thus,

$$f_\gamma = \tau_{pp}/(\tau_{pp}+\tau_c) \simeq 0.37 \text{ for } 10^{17} \lesssim E \lesssim 10^{19} \qquad (22)$$

From equations (16), (17) and (21), we find that the mean rate from the two-stage process is given approximately by

$$u(E_\gamma) \simeq 1.2\delta_{pp}(E_\gamma)E_\gamma c/\lambda_{pp}(E_\gamma) \qquad (23)$$

Substituting equations (11) and (16) in equation (23) and equations (22 and (23) in Equation (20) we find

$$I_\Sigma(E_\gamma) \simeq \frac{Q_\gamma L_\Sigma}{4\pi}\,\xi(E_\gamma)\begin{cases} \Gamma/(\Gamma-1) - (E_\gamma/E_1) & ,E_\gamma \leq E_1 \\ [1/(\Gamma-1)]\,(E_\gamma/E_1)^{-(\Gamma-1)} & ,E_\gamma > E_1 \end{cases} \qquad (24)$$

where

$$\xi(E_\gamma) = (\log_{10}E_\gamma - 14.75)/(\log_{10}E_\gamma - 15.97)$$

and $L_\Sigma \approx 5.9\text{x}10^{25}$cm.

Equations (18) and (24) are valid in the energy region where the 2.7K radiation field is the dominant source of target photons and where the production of muon pairs is unimportant, i.e., for $E_\gamma < 10^{19}$eV. Wdowczyk et al. (1972) have determined that for $10^{19} < E_\gamma < 10^{20}$eV $\lambda_{pp}(E_\gamma) \simeq 10^{25}$ cm ≃ const. Thus, in this energy range, equations(18) and (24) are overestimates and have to be corrected for these additional absorption processes. Also, in equation (24) we have neglected the additional contribution of the lower energy electrons produced in the pair-production process. This correction becomes important at lower energies where, e.g. equation (24) underestimates $I_\Sigma(E_\gamma)$ by a factor of ~ 2 at $E_\gamma = E_1/\delta_{pp}(E_1) \simeq E_1/20 \simeq 2.4 \times 10^{18}$eV. Estimates of the above corrections have been made to equations (24) and the resultant γ-ray spectra obtained for the ultrahigh energy primary spectra given by Linsley, (1962), and Andrews, et al. (1971) are shown in figures (1) and (2). To the extent of their validity, the results of figures (1) and (2) confirm the numerical calculations and conclusions first obtained by Wdowczyk, et al. (1972) for photon spectra in the energy region $10^{18} \lesssim E_\gamma \lesssim 10^{20}$eV.

The effect of magnetic fields on the cascade process was also pointed out by Wdowczyk, et al. It becomes important when the electron energy loss rate due to synchrotron radiation in intergalactic space is greater than or equal to that due to Compton interactions, a condition fulfilled when

$$B_{ig} \gtrsim 1.3 \times 10^{-11} \; (E_1/E_e) \text{ gauss} \tag{25}$$

A recent discussion of the possible intensity of intergalactic magnetic fields has been given by Brecher and Blumenthal (1970). Using their arguments, but with the new value of the Hubble constant of 50 km/s/Mpc, it follows that if the general galactic magnetic field condensed out of the intergalactic field then $B_{ig} > 10^{-10}$ gauss. However, if the contrary is true and intergalactic fields result from expansion of galactic fields then $B_{ig} < 10^{-8}$ gauss. A proper determination can only be made empirically and the empirical upper limit on the intergalactic field based on determination of the rotation measure for distant radio sources is

$$B_{ig} \lesssim 2 \times 10^{-10} \text{ gauss} \tag{26}$$

Thus, from equations (25) and (26) it follows that the cascade process may or may not be cut off at energies greater than or equal to 3×10^{18} eV depending on the exact value of the average intergalactic magnetic field.

However, the galactic magnetic field has a much more predictable effect on the ultrahigh energy electrons which make up $1-f_\gamma \simeq 63\%$ of the electromagnetic cascade. These electrons have to travel through at least half the thickness of the galactic disk $\simeq 6.5 \times 10^{20}$ cm spending $\simeq 2 \times 10^{10}$ s in the galactic disk with a mean field of $\sim 3\times10^{-6}$gauss. This is enough time to reduce the energy of any electron with $E_e >> 10^{15}$eV to an energy of $\simeq 10^{15}$eV (out of our region of interest) by synchrotron radiation losses. Thus, regardless of the strength of the intergalactic magnetic field, the galactic field strength ensures the elimination of all ultrahigh energy electrons from the cascade before reaching the earth.

The electron and neutrino flux from the decay of charged pions produced in photomeson interactions will now be estimated. Again, the main contribution is dominated by the channel

$$\gamma + p \rightarrow \Delta(1238) \rightarrow \begin{cases} n + \pi^+ & \text{Prob.} = 1/3 \\ p + \pi^o & \text{Prob.} = 2/3 \end{cases} \tag{27}$$

and thus for rough estimates we take

$$\sigma_+ \simeq \frac{1}{2}\sigma_o \simeq 10^{-28}\text{cm}^2 \tag{28}$$

The decay of the π^+ meson results in a positron and three neutrinos all with an average energy $\sim$35MeV. The positrons represent an additional contribution to the electromagnetic cascade flux of the order of 10-20%. The neutrinos provide a source spectrum of the form similar to eequation (9) but with E_1 replaced by $E_{\nu_1} \simeq E_1/2$ and with

$$Q_\nu \simeq \frac{3}{2} Q_\gamma \tag{29}$$

so that at high energies $E \gtrsim E_1$,

$$\frac{Q(E_\nu)}{Q(E_\gamma)}\Bigg|_{E_\nu=E_\gamma=E} \simeq \frac{3}{2}\,\frac{(E_\gamma/E_1)^{-\Gamma}}{(E_\nu/2E_1)^{-\Gamma}} \simeq \frac{3}{16} \tag{30}$$

The resultant neutrino flux is given by

$$I(E_\nu) = \frac{Q(E_\nu)}{4\pi} R_u \simeq 12.5 I(E_p) \text{for } E_\nu = E_p > 2.4\times10^{19}\,\text{eV} \tag{31}$$

where $R_u = 10^{28}$ cm is the radius of the universe since the universe is fully transparent to neutrinos. This possible large flux of high energy neutrinos has been suggested by Berezinsky and Zatsepin (196 9 a, b) to be a possible explanation for air-shower events of energy greater than 10^{20} eV if the neutrino interaction cross section becomes comparable to that of hadrons at these energies. Such an explanation is needed if these events are to be of extragalactic origin since the cosmic-ray proton spectrum is expected to cut off at $E_p \simeq 10^{20}$ eV (Greisen 1966, Zatsepin and Kuzmin 1966, Stecker 1968). Assuming then that the neutrino inelastic cross section rises linearly with energy and is given by (Krishnaswamy et al., 1971; Bjorken and Paschos 1970, Pattison 1970)

$$\sigma_\nu \simeq 10^{-38}\, E_{GeV} \simeq 3\times10^{-22}\sigma_{p,inel} E_{eV} \tag{32}$$

we find

$$\frac{\sigma_\nu}{\sigma_p} = \frac{1}{12.5} \text{ at } E \simeq 2.5\times10^{20}\,\text{eV} \tag{33}$$

Since the extragalactic proton spectrum should drop off at 10^{20}eV and the nutrino event rate $\sim\sigma_\nu I_\nu$, the event rates for neutrino induced and cosmic-ray induced showers may become comparable in the 10^{20}eV energy range but with a predicted flattening in the spectrum by one power at the higher energies. The transition energy may be somewhat lower depending on the exact values of Γ and σ_ν and the role of cosmological neutrinos. (See discussion of Berezinskỳ and Zatsepin 1969b and Stecker 1971*).

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*In a previous paper (Stecker 1971), the author considered the cosmological neutrino hypothesis unaware the Berezinskỳ and Zatsepin (1969b) had ruled out the same form of that hypothesis on the same grounds in a reexamination of their earlier paper (Berezinsky and Zatsepin 1969a. Those arguments do not apply to the non-cosmological neutrinos discussed here and by Berezinsky and Zatsepin. The critical test for the non-cosmological neutrino hypothesis lies in a flattening of the ultrahigh energy air-shower spectrum which may (Linsley 1962) or may not (Andrews, et al. 1971) exist.

In conclusion, it appears that it may yet be quite some time before the uncertainties regarding the various possible components of the ultrahigh energy cosmic radiation are finally resolved, but the following points may be made:

1. The presence of photons making up a few per cent of the total flux at 10^{19} eV would imply a universal flux of both blackbody photons and ultrahigh energy cosmic-ray nucleons and also indicate that the intergalactic magnetic field has an average value less than $\sim 10^{-11}$ G. On the contrary, the absence of a significant 10^{19} eV photon flux does not rule out the universal ultrahigh energy cosmic-ray hypothesis since it may only indicate the presence of intergalactic magnetic fields $> 10^{-11}$ G.

2. Ultrahigh energy electrons are not expected to reach the earth because of synchrotron radiation losses in the galactic magnetic field.

3. The establishment of evidence for a large ultrahigh energy neutrino flux would indicate the presence of both ultrahigh energy cosmic-rays and black-body radiation throughout the universe. The absence of neutrino events (with such events evidenced by a flattening in the air-shower energy spectrum) may only indicate that σ_ν does not rise linearly with E_ν up to the highest observed energies.

4. The presence of a continuing straight primary spectrum above 10^{20} eV would indicate a local origin for these particles either in the galaxy (Syrovatsky 1971, Stecker 1971) or in the local supercluster (Stecker 1968, Brecher and Burbidge 1971), or (least likely) the absence of a universal blackbody radiation field. In the case of galactic origin, the ultrahigh energy cosmic-rays are expected to be heavy nuclei (Stecker 1971). Some evidence for this

has been summarized previously (Stecker 1971); more recent evidence that the ultrahigh energy cosmic-rays may be heavy nuclei comes from a reexamination of the Volcano Ranch data (Linsley 1972, private communication) and a recent suggestion by Wdowczyk and Wolfendale (1972) based on the scaling hypothesis (Feynman 1969).

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Figure Captions

Figure 1. Cosmic-Ray Photon Cascade spectrum (I_Σ) and first generation spectrum (I_1) for a primary spectrum (I_p shown) of

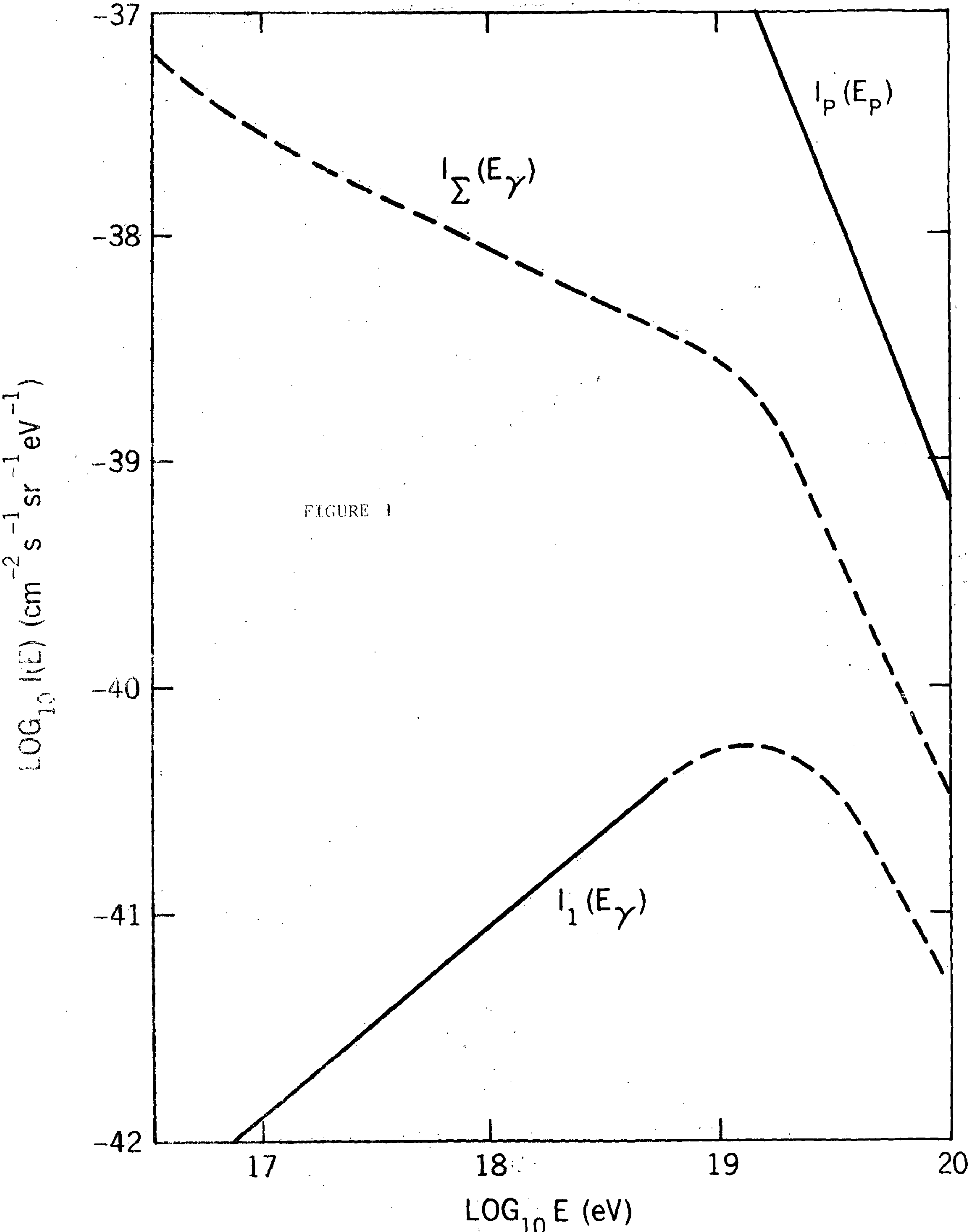
$$I_p(E_p) = 6.4\times10^{-40}(E_p/10^{20})^{-2.6} \quad (\mathrm{cm}^2\cdot\mathrm{s}\cdot\mathrm{sr}\cdot\mathrm{eV})^{-1}$$

(Linsley 1962).

Figure 2. Cosmic-ray Photon Cascade spectrum (I_Σ) and first generation spectrum (I_1) for a primary spectrum (I_p shown) of

$$I_p(E_p) = 2.4\times10^{-40}(E_p/10^{20})^{-3.24} \quad (\mathrm{cm}^2\cdot\mathrm{s}\cdot\mathrm{sr}\cdot\mathrm{eV})^{-1}$$

(Andrews,et al. 1971).



-37
-38
-39
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-41
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17
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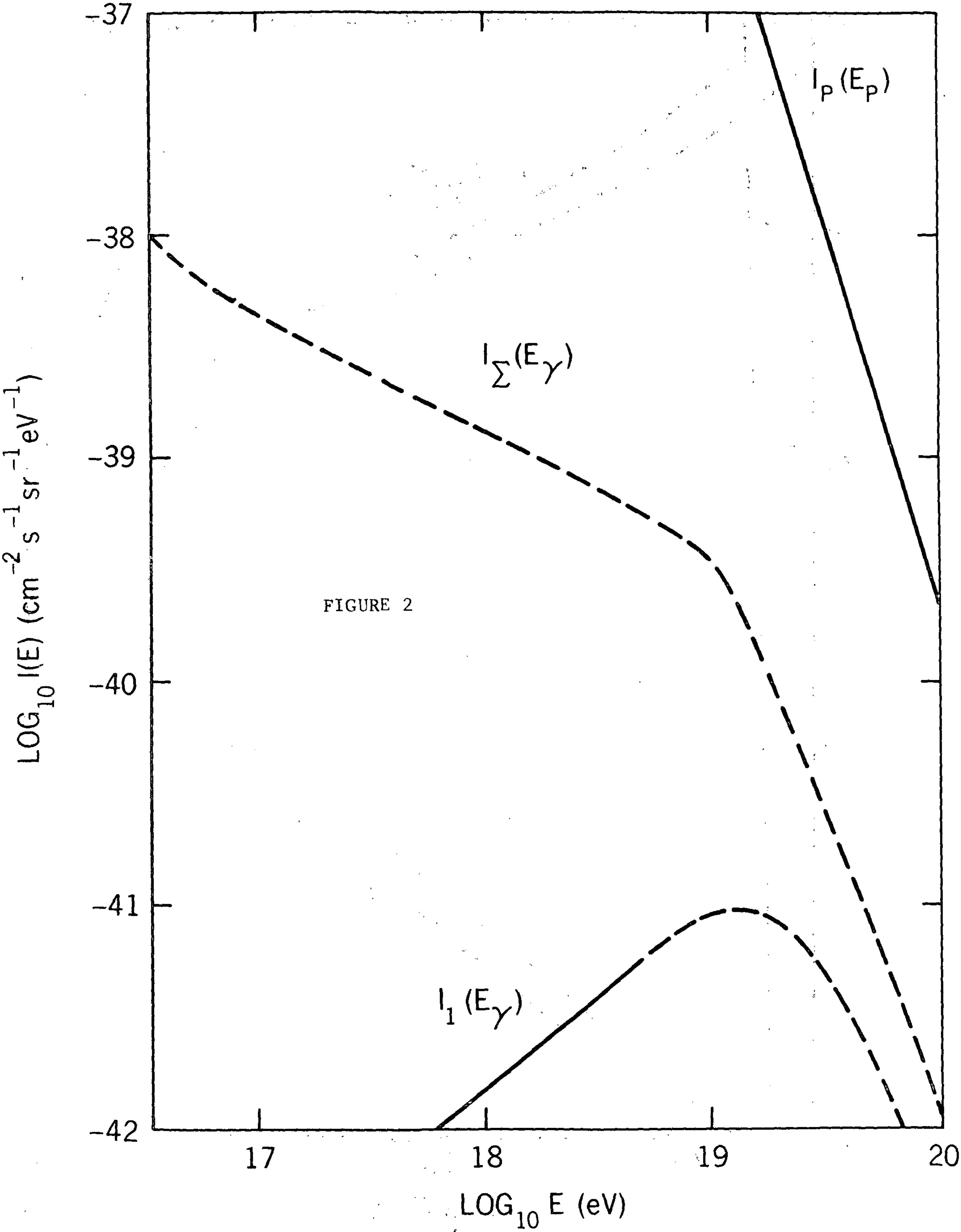
19
20
$I_P(E_P)$
$I_\Sigma(E_\gamma)$
$I_1(E_\gamma)$
$LOG_{10}\ I(E)\ (cm^{-2}s^{-1}sr^{-1}eV^{-1})$
$LOG_{10}\ E\ (eV)$

FIGURE 1



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$I_p(E_p)$
$I_\Sigma(E_\gamma)$
$I_1(E_\gamma)$
$LOG_{10}\, I(E)\ (cm^{-2}\, s^{-1}\, sr^{-1}\, eV^{-1})$
$LOG_{10}\, E\ (eV)$

FIGURE 2