# ENERGY SPECTRUM OF EXTRAGALACTIC GAMMA-RAY SOURCES

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1. *INTRODUCTION.* Soon after the discovery of the cosmic microwave background radiation it was pointed out that $\gamma$-rays above $10^{14}$ eV would be attenuated by photon-photon pair production interactions with photons of the cosmic background (Jelley, 1966; Gould and Schreder, 1966, 1967a). Other processes, e.g. double pair production (Brown *et al.*, 1973), can also be important at extremely high energies. Later, it was realised that if the intergalactic magnetic field was low then $\gamma$-rays above $10^{14}$ eV might still reach Earth from extragalactic distances through an electron-photon cascade involving pair production and inverse Compton (IC) interactions (Bonmetto, 1971; Bonmetto and Lucchin, 1971; Allcock and Wdowczyk, 1972; Wdowczyk *et al.*, 1972; Stecker, 1973; Gould and Rephaeli, 1978). In many of these calculations, only the highest energy electron or photon produced in an interaction was considered in order to reduce the problem from a cascade calculation to a simpler one of calculating the energy loss rate of the "high energy particle".

Recently, Clay *et al.* (1984) reported an excess of EAS above $\sim 10^{15}$ eV from the direction of Cen A. At first sight, it seems unlikely that the excess could be due to $\gamma$-rays as Cen A is about 6 Mpc away, more than 600 times the interaction length of $10^{15}$ eV photons with the 3 K microwave background radiation. Subsequently UHE $\gamma$-rays above $10^{16}$ eV have been observed from another extragalactic source, LMC X-4, in phase with its $1.408^{d}$ orbital period (Protheroe and Clay, 1985). This object is in the Large Magellanic Cloud at a distance of $\sim$50 kpc, i.e. about 5 interaction lengths away. With this recent extension of extragalactic astronomy to photon energies in excess of $10^{14}$ eV, it is therefore timely to re-examine the extragalactic propagation of $\gamma$-rays in detail. Here I report the result of Monte Carlo electron-photon cascade calculations for propagation of $\gamma$-rays through regions of extragalactic space containing no magnetic field. These calculations then provide upper limits to the expected flux from extragalactic sources.

2. *THE SIMULATION.* Since we are interested primarily in $\gamma$-rays in the $10^{14}$-$10^{17}$ eV energy range, I have only considered interactions of electrons and photons with the 3 K microwave background radiation. As mentioned above, to obtain an upper limit to the expected $\gamma$-ray flux from sources, I have assumed that the intergalactic field is so low that it can be ignored (i.e. $\ll 10^{-7}$ gauss). Interactions with photons of the near-infrared background radiation (Matsumoto *et al.*, 1983; de Bernadis *et al.*, 1985) are not considered here although these will have important implications for $\gamma$-rays below $10^{14}$ eV if the near-infrared background radiation is universal (this topic is discussed later). Interaction lengths of electrons and photons in the microwave background radiation at a temperature of 2.96 K (Narlikar, 1982) have been calculated and are given in Fig. 1. For photon-photon interactions, this is based on the results of Gould and Schreder (1967b) together with the correction by Gould (1983) and, for IC interactions, on an integration over the full Klein-Nishina cross sections (Jauch and Rohrlich, 1976).

Full Monte Carlo simulations of the electron-photon cascade involving photon-photon pair production interactions and IC interactions of electrons with the 3 K background were then performed using the exact cross sections. Full details of the calculation will be published elsewhere (Protheroe, 1985).

To run the Monte Carlo simulation program over very large distances (e.g. greater than ~200 kpc) would take excessive computer time. To get around this problem, the simulation was run over a smaller distance, $\Delta x$, in order to obtain matrices $[A(\Delta x)]$, $[B(\Delta x)]$, $[C(\Delta x)]$, and $[D(\Delta x)]$ which describe the evolution of arbitrary electron and photon spectra after propagation through distance $\Delta x$ of extragalactic space. The energy spectra of photons and electrons at distance x from the source, $F_\gamma(E,x)$ and $F_e(E,x)$, are represented by column vectors $f^\gamma(x)$ and $f^e(x)$ whose elements are defined by

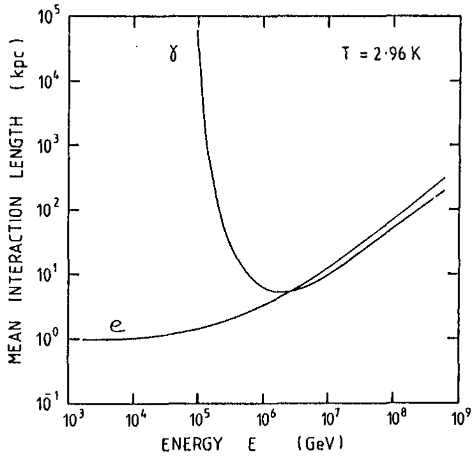


Fig. 1. Mean interaction length of electrons and γ-rays in a 2.96 K black body radiation field.

$$f^\gamma_k(x) = \int_{E_k}^{\alpha E_k} F_\gamma(E,x)\, dE \qquad (1)$$

and

$$f^e_k(x) = \int_{E_k}^{\alpha E_k} F_e(E,x)\, dE \qquad (2)$$

where $\alpha = E_{k+1}/E_k$. The spectra of photons and electrons after traversing a further distance $\Delta x$ are then obtained from

$$f^\gamma(x+\Delta x) = [A(\Delta x)] f^\gamma(x) + [B(\Delta x)] f^e(x) \qquad (3)$$

$$f^e(x+\Delta x) = [C(\Delta x)] f^\gamma(x) + [D(\Delta x)] f^e(x) \qquad (4)$$

where $A(\Delta x)_{kj}$ is the mean number of photons produced with energies in the range $E_k$ to $\alpha E_k$ as a result of an electron-photon cascade through distance $\Delta x$ initiated by an "average" photon with an energy in the range $E_j$ to $\alpha E_j$. The elements of $[B(\Delta x)]$, $[C(\Delta x)]$, and $[D(\Delta x)]$ are defined in a similar way for the appropriate primary and secondary species.

In the present simulation, $E_1$=100 GeV, $\alpha=10^{0.1}$, and 90 energy bins were used. For each primary energy, e.g. bin k, 400 primary γ-rays were sampled from an $E^{-2}$ differential spectrum in the range $E_k$ to $\alpha E_k$ and for each primary γ-ray a full Monte Carlo calculation was carried out over a distance $\Delta x$=50 kpc. The secondary photons and electrons reaching distance $\Delta x$ having energies in bin j were then divided by 400 to obtain $A(\Delta x)_{kj}$ and $B(\Delta x)_{kj}$ respectively. An identical method was adopted for primary electrons to obtain $C(\Delta x)_{kj}$ and $D(\Delta x)_{kj}$.

3. *RESULTS*. The differential and integral energy spectra of γ-rays

expected at various distances ranging from 50 kpc to 6.4 Mpc from a source which emits an $E^{-2}$ differential $\gamma$-ray spectrum are shown in Fig. 2 for two extreme assumptions about the intergalactic magnetic field.

The spectra corresponding to a distance of 6.4 Mpc would apply to Cen A. Clearly, if cascading takes place then $\gamma$-rays at $10^{15}$-$10^{16}$ eV energies could reach Earth. To see what primary $\gamma$-ray energies (i.e. at the source) would produce $\gamma$-rays which would be observed in this energy range, the spectrum expected from a monoenergetic source of $\gamma$-rays at a distance of 6.4 Mpc has been calculated for various primary energies in the range $10^{15}$-$10^{19}$ eV. The result is shown in Fig. 3 and indicates that $\gamma$-rays at $10^{15}$-$10^{16}$ eV energies from a source at 6.4 Mpc distant would be due to primary $\gamma$-rays of energy $\sim 10^{18}$ eV.

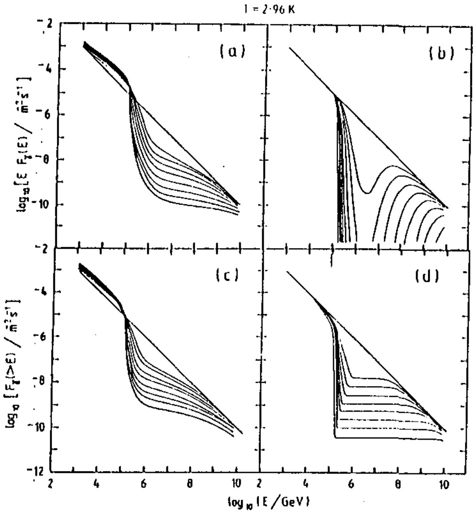


Fig. 2. Expected differential (a and b) and integral (c and d) energy spectra of $\gamma$-rays at distances of 0, 50, 100, 200, 400, 800 kpc, 1.6, 3.2 and 6.4 Mpc from a source emitting an $E^{-2}$ differential spectrum of $\gamma$-rays (the curves are not labelled but may be identified as in each case the flux at $10^{6}$ GeV decreases monotonically as distance is increased). (a) and (c) are for zero magnetic field conditions in which cascading is unimpeded; (b) and (d) are for high field conditions. (N.B. curves do not take account of the inverse-square law).

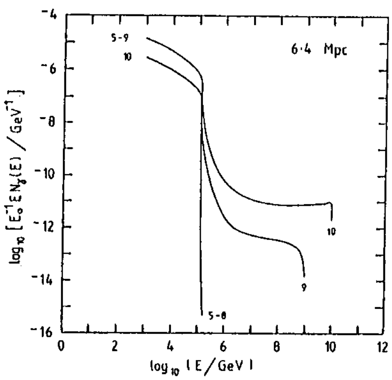


Fig. 3. Average differential energy spectrum expected at Earth from a source at a distance of 6.4 Mpc emitting monoenergetic $\gamma$-rays. The curves do not take account of the inverse-square law and are normalised to one primary $\gamma$-ray and are divided by the primary energy, $E_0$. (Numbers attached to the curves are $\log_{10}[E_0/\mathrm{GeV}]$).

4. *DISCUSSION*. Sources in the Magellanic Clouds, or in other galaxies of the local group, should have energy spectra which display an absorption feature at $10^{14}$-$10^{16}$ eV energies together with a peak just below $10^{14}$ eV. The peak just below $10^{14}$ eV could make observing in this energy range quite attractive. The shape of the spectrum contains information on *both* the magnetic field *and* the column density of microwave photons, i.e. the relative heights of the peak and dip will depend on the magnetic field and distance to the source. If the energy spectra could be accurately mapped out, the depth of the absorption feature together with the height of the peak could then possibly be used to measure *both* the distance to the source *and* the average strength of the magnetic field along the line of sight to the source. It is thus possible, in principle at least, to obtain information about the radiation content and magnetic field in intergalactic space within the local group by studying the energy spectra of $\gamma$-ray

sources.

It is clear from Fig. 2(a) that it *is* possible for $\sim 10^{18}$ eV $\gamma$-rays to reach Earth from Cen A provided the intergalactic magnetic field is low enough. Even then, however, the flux is down by $\sim 10^{-3}$ of that we would receive if the cosmic microwave background radiation were not present. For the observed excess of air showers from the *direction* of Cen A (Clay *et al.*, 1984) to be due to $\gamma$-rays *from* Cen A, either the microwave background radiation must not be universal or Cen A must be much more luminous at $\sim 10^{18}$ eV energies than at lower energies. It would have to have a luminosity per decade at $\sim 10^{18}$ eV comparable to that of 3C273 at lower energies. A third possibility is that a foreground source in our Galaxy is being observed. Clearly, additional observations of Cen A are urgently required.

There has recently been an observation (Matsumoto *et al.*, 1983) of a dilute near-infrared background radiation. If the near-infrared photon energy density is as high as suggested and is universal then sources more distant than any in the local group of galaxies would show energy spectra strongly attenuated below $10^{14}$ down to $\sim 10^{12}$ eV (see also Rana and Wolfendale, 1984). A peak in the energy spectrum would not then be apparent at just below $10^{14}$ eV for these sources but might occur instead at just below $10^{12}$ eV. This could be the explanation for the somewhat higher than expected (on the basis of extrapolation from hard X-ray energies through 100 MeV upper limits; see e.g. the survey by Baitty *et al.*, 1981) $\gamma$-ray flux from Cen A observed by Grindlay *et al.* (1975) at these energies.

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