High Energy Electrons and Emission of the Omnidirectional Synchrotron Radiation in Radio Frequency and X-Ray Regions*

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ABSTRACT

The recent measurements of the flux and differential energy spectrum of primary electrons in the 0.2 BeV to 300 BeV energy region made near the recent solar minimum period (1966) are summarized. These measurements are consistent with a change in the exponent of the power law spectrum of primary electrons from 1.6 ± 0.15 to 2.6 ± 0.15 at about 2 to 5 BeV. We wish to point out that the observations of the omnidirectional intensity and the spectrum of the non-thermal radio frequency background radiation above 200 MHz are consistent with this steepening of the electron energy spectrum. Furthermore radio observations in the 10 MHz to 100 MHz region are in agreement with the lower energy electron spectrum corresponding to these radio frequencies (0.2 to 2 BeV) within 50%. This indicates that the residual solar modulation of electrons in the 0.2 to 2 BeV energy region is not large.

If we assume that the electron energy spectrum extends in the form of a power law up to about $\sim 10^5 - 10^6$ BeV with the exponent (2.6, 2.8 or 3.0), then the synchrotron emission of these ultra high energy electrons would contribute to the recently observed diffuse component of cosmic X-rays although it does not completely account for the large flux. This assumed electron spectrum would also give a possible explanation for the observation of a small number of air showers which may have been produced by the electron or photon component of the primary cosmic rays.

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1. Synchrotron Radiation in the R. F. Region:

In an earlier paper Verma (1967) (hereinafter called Paper I) has suggested that the primary electron energy spectrum in the 1 to 30 BeV energy range, observed in the summer of 1965 in balloon experiments, has a change in slope at roughly around 7 - 10 BeV. In Fig. 1 we have summarized the measurements of the flux and energy spectrum of primary electrons taken in 1963 (Daniel and Stephens 1966) and in the summer of 1966 (L'Heureux and Meyer 1967; Bleeker, Burger, Deerenburg, Scheepmaker, Swanenburg, and Tanaka 1967b). These measurements confirm the presence of a change in the slope, though it occurs around 2 - 5 BeV. This change in the slope is expected to occur at some critical energy E_c where the energy losses proportional to E^2 (synchrotron and Compton losses) are equal to the energy loss proportional to E (leakage loss). Equating these two kinds of energy loss rates we get:

$$b E_c^2 = \frac{E_c}{\tau} \quad \text{or} \quad \tau = \frac{1}{b E_c} \tag{1}$$

where b is a constant and τ is the leakage lifetime of the electrons (same parameters as defined in Paper I). Using the value of $b \cong 10^{-25}$ (eV sec)$^{-1}$ as in Paper I and the revised value of $E_c \cong 3.5$ BeV, we obtain the lifetime $\tau = (3 \sim 4) \times 10^{15}$ sec, slightly larger than the value suggested earlier. The data in Fig. 1 can be represented as power law spectra in energy: $\frac{dJ}{dE} = K E^{-\gamma}$ electrons/m^2-sec.-sterad-BeV where $K = K_1 = 30; \; \gamma = \gamma_1 = 1.6 \pm .15; .2 < E < 2 \text{ BeV} \quad (2)$

$= K_2 = 130; \; = \gamma_2 = 2.6 \pm .15; \; 5 < E < 350 \text{ BeV} \quad (3)$

If we assume that the residual solar modulation of electrons in 1966 is negligibly small then the equilibrium electron energy spectrum outside the solar system and even in the halo region can be assumed to be given by Eqns. (2) and (3). First we will show that nonthermal radio frequency observations in the 10 MHz to 200 MHz region are in agreement with the observed electron energy spectrum(0.2 to 2.0 BeV). This comparison also gives some idea about the residual solar modulation, which we discuss in Section II. In the framework of the galactic halo model, we assume that the average intensity of the halo magnetic field $\langle H \rangle$ is 3×10^{-6} gauss and the radius of the halo region " L " is about 15 Kpc (as assumed in Paper I). Electrons in the halo having energy between 0.2 BeV and 350 BeV will emit synchrotron radiation in the R. F. to microwave regions. Most of the power will fall in the 10 MHz to 10^5 MHz frequency interval. The flux and frequency spectrum of the synchrotron radiation in the 10 to 1000 MHz frequency interval are calculated, using the formula:

$$I(\nu) = a_1(\gamma) \; a_2 L K \langle H \rangle^{(\gamma+1)/2} \left(6.26 \times 10^{18}/\nu \right)^{(\gamma-1)/2} \text{ Photons/cm}^2\text{.sec.ster.Hz.} \quad (4)$$

(Ginzburg and Syrovatski, 1965), where $a_1(\gamma)$ and a_2 are constants.

In Fig. 2 we summarize the measurements of the nonthermal radio frequency background radiation in the 10 MHz to 1000 MHz frequency region. In the same figure the flux and frequency spectrum of synchrotron radiation calculated on the basis of the electron spectrum is plotted (dashed line $\eta = 0$). The measurements by Purton (1966) have errors smaller than the size of the circles. He obtained the intensities at various frequencies relative to that at 81.5 MHz by recalibration of the measurements of Turtle *et al.* (1962). There seems to be reasonable agreement between the calculated spectrum (dashed line $\eta = 0$) and the measurements of Purton and Turtle *et al.* (1962). Penzias and Wilson (1966) have observed the radio spectrum above 400 MHz near the disc region. By comparing their measurements with earlier measurements at lower frequencies, the authors obtained a brightness spectral index "α" of 0.9 (temperature spectral index 2.9). As a consequence, the electron spectrum ($\gtrsim$ 10 BeV) should have a slope γ ($= 2\alpha + 1$) of 2.8 which is in agreement with the measured value of the slope of the electron spectrum $\gamma_2 = 2.6 \pm 0.15$, Eqn. (3). Above 1000 MHz the 3° K thermal radiation is the major contributor (Fig. 2, solid line), and synchrotron radiation in this frequency region is difficult to observe.

II. Estimate of Residual Solar Modulation of Electrons:

Below 81.5 MHz the flux of synchrotron radiation calculated on the basis of the electron spectrum agrees with the measurements of Turtle *et al.* (1962) and Purton (1966) but is about 50% less than that observed by Shain and Higgins (1954) and Wielbinski and Yates (1965). From this comparison we infer that there may exist a residual modulation of electrons in the 0.2 BeV to 2 BeV energy region at the present solar minimum time, but if so it seems to be small as will be discussed below. The agreement at higher energies indicates that the value of $\langle H \rangle^{(\gamma+1)/2} L$ assumed above is quite reasonable.[1]

O'Gallagher and Simpson (1967) and O'Gallagher (1967) have studied the dependence of the intensity variations with heliocentric distance of protons and helium nuclei as a function of magnetic rigidity and velocity. They found that the radial gradient could be described by a $1/\beta$ dependence below ~ 1 BV and $1/R\beta$ dependence above R ~ 1-2 BV. Balasubrahmanyan et al. (1967), Gloeckler and Jokipii (1966) showed that the time variation of intensity of proton and helium nuclei due to solar modulation have the same rigidity and velocity dependence. If we apply this modulating function to the electron spectrum observed at Earth to obtain the spectrum outside the solar system, we have to use

$$\left(\frac{dJ}{dE}\right)_{\infty} \Big/ \left(\frac{dJ}{dE}\right)_{E} = \exp(\eta / R\beta) \qquad \text{for } E \gtrsim 2\,\text{BeV}$$

$$= \exp(\eta / R_0\beta) \qquad \text{for } E \lesssim 1\,\text{BeV} \tag{5}$$

where $\left(\frac{dJ}{dE}\right)_E$ is the electron energy spectrum observed at Earth and $\left(\frac{dJ}{dE}\right)_\infty$ is the spectrum outside the solar system. R_0 is constant and η is the modulation parameter which does not depend on particle parameters. For electrons, in the energy region of interest here, the energy E in BeV is equal to the magnetic rigidity R in BV.

We find after application of Eqn. (5), that the electron spectrum in the high energy region (Eqn. 3) does not change much while the spectrum (Eqn. 2) changes

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[1] The value of $\langle H\rangle^{(\gamma+1)/2} L$ used here is probably the upper limit, for the reason that part of the radio frequency background radiation, which is assumed to be coming from the halo region, could be of extragalactic origin and/or originate in the galactic disk.

appreciably in the low energy region. We show these "demodulated" electron spectra for $\eta = 0.3$ and 0.5 by dashed lines in Fig. 1. Using these electron spectra we have evaluated the synchrotron radiation emitted in the R.F. region for two cases. We plotted these in Fig. 2 to show that these are consistent with the radio observation within errors. Thus a residual solar modulation of electrons of zero ($\eta = 0$) to about 65% ($\eta = 0.5$) in the 0.2 BeV to 2.0 BeV energy region, in 1966, is consistent with the radio measurements. In Figure 2 we also show the calculated spectra of the synchrotron radiation for the lower value of $\langle H \rangle = 2 \times 10^{-6}$ gauss and for various demodulated electron spectra ($\eta = 0$, 0.3 and 0.5). It is clear that one cannot obtain agreement between observation and calculation using low values of $\langle H \rangle$ and various values of η . Recently L'Heureux, Meyer, Verma and Vogt (1967) have reported measurements of the intensity of the primary electrons from 1960 through 1966, and found no long term time variation (an upper limit for the increase of the flux of about 60%) in the 0.25 BeV to 1 BeV energy interval. Bleeker, Burger, Deerenberg, Scheepmaker, Swanenburg and Tanaka (1967c), and L'Heureux and Meyer (1967) observed no change of the electron flux (an upper limit for the decrease of the flux of about 20%) in the 0.25 BeV to several BeV energy interval between 1965 and 1966. Beedle and Webber (1967) reported a decrease of 30 - 50% in the intensity of electrons of energy less than 1 BeV, between 1965 and 1966. While these experiments do not lead to a direct statement concerning the residual modulation at solar minimum, they imply, with the exception of Beedle and Webber (1967) results, that the residual modulation must be small, if one assumes the current modulation models to be correct.

III. Synchrotron Radiation in the X-Ray Region:

In recent years the diffuse X-ray intensity has been measured in the 1 KeV to 1000 KeV energy region. These measurements were made in various directions in galactic longitude and latitude. In Fig. 3 we summarize the results. The X-ray intensity is roughly isotropic. Hoyle (1965), Gould (1965), Fazio, Stecker and Wright (1966) tried to account for the diffuse component of X-rays by Compton scattering of low energy photons ($3^{o}K$) by the galactic relativistic electrons. Recently Felten and Morrison gave an explanation of the flux and spectrum of the X-rays by considering the Compton scattering of starlight and $3^{o}K$ radiation with halo electrons. These processes do not provide a sufficient X-ray intensity. Felten and Morrison therefore proposed a homogeneous metagalactic model in which electrons are assumed to be present in galaxies and also in the intergalactic regions. They calculated an electron spectrum required in the intergalactic region which would produce the observed X-ray spectrum through the inverse Compton scattering of electrons with the photons of the $3^{o}K$ black-body radiation.

In this paper we consider another possibility, namely that the observed X-ray intensity in the 1 KeV to 400 KeV energy region could partly be explained as synchrotron emission of ultra high energy halo electrons. This was earlier suggested by Clark (1963), and Ginzburg and Syrovatskii (1964). In Fig. 4 we again plotted the observed energy spectrum of electrons in the 10 BeV to 350 BeV energy region and carried out an extrapolation to obtain the spectrum in the 10^{2} BeV to 10^{6} BeV energy region with various exponents $\gamma = 2.6, 2.8$ and 3.0. Such an equilibrium electron energy spectrum will require a flat injection spectrum up to energies as high as 10^{6} BeV, which is very difficult to understand. But to obtain an upper limit of synchrotron radiation in the X-ray region, we assumed such an equilibrium spectrum for the electrons. By assuming this spectrum we also provide a possible explanation, as discussed below, for the observation of a small number of air showers which are believed to have been produced by electrons or photons of the primary cosmic rays.

In the last few years Toyoda, Suga, Murakami, Hasagawa, Shibata, Domingo, Escobar, Kamata, Bradt, Clark, and LaPointe (1965) (Bolivian Air Shower Joint Experiment) and Gawin, Hibner, Wdowczyk, Zawadzki and Maze (1965) have observed that a small fraction of air showers have very low abundance of muons. They interpret these air showers to be produced by either electrons or photons. We made an estimate of the electron flux under the assumption that these showers are produced by electrons. The resulting flux values are shown in Fig. 4 together with various cases of the extrapolations of the electron spectrum up to 10^6 BeV. (Because of large synchrotron losses, these electrons cannot travel distances larger than a Kpc. in the halo region.) As a consequence such high energy electrons will be confined in the halo region near the galactic disc. Then it is natural that the synchrotron radiation, emitted by ultra high energy electrons (10^4 BeV to 10^6 BeV) in the halo magnetic field (3×10^{-6} gauss), fall in the X-ray energy region of about 1 KeV to 400 KeV and should be anisotropic. In Fig. 3 we compare the calculated synchrotron X-ray spectrum with the observed energy spectrum of X-rays. Even though the calculated intensity of the synchrotron X-rays, using the electron spectrum with the slope, γ = 2.6, 2.8 and 3.0, is smaller than the observed intensity, the shape of the spectrum seems to agree quite well with observations. The synchrotron X-rays might be distinguished from X-rays produced by other processes, since they would be polarized if the halo magnetic fields were homogeneous on a large scale. Furthermore, the flux of these X-rays would be larger from the direction of the galactic center than from the anti center or polar regions. Since the measurements indicate that the anisotropy of the diffuse X-rays is small, the synchrotron Xpray contribution is also small in agreement with this calculation. We have also plotted the spectrum of metagalactic Compton X-rays of Felten and Morrison in Fig. 3 as dash-dot-dash line.

IV. Conclusion

Using the electron spectrum near the present solar minimum period, we calculated the intensity and the spectrum of the synchrotron radiation produced in the galaxy. We show that the electron flux and spectrum are in agreement with the nonthermal radio background observations from the halo region of our galaxy. The primary electron power law energy spectrum changes exponent from 1.6 to 2.6 around ~ 2 - 5 GeV which implies a leakage lifetime for electrons of $\sim 3 \times 10^{15}$ sec. The nonthermal radio background measurements are consistent with the absence or a maximum of 65%, of residual solar modulation of electrons from 0.2 to 2 BeV at the present solar minimum.

If ultra high energy electrons (10^3 BeV to 10^6 BeV) exist in the galactic halo, with a spectrum given by $dJ/dE = 130\ E^{-\gamma}$ electrons/ (m^2 sec ster BeV) and $2.6 < \gamma < 3.0$, then only 10 percent (or less) of the observed omnidirectional intensity and spectrum of X-rays may be interpreted as being produced by the emission of synchrotron radiation by ultra high energy galactic electrons ($10^4 - 10^6$ BeV). Most of the X-ray intensity may be produced by Compton scattering of starlight and 3°K thermal photons with metagalactic high energy electrons.

Measurements of the electron spectrum in the 10^2 BeV to 10^6 BeV energy region are very desirable. If it turns out to be that the electron spectrum is steeper than the one assumed here, then most of the conclusions discussed above remain unchanged except the synchrotron emission by ultra high energy electrons in the X-ray region will be negligibly small. An attempt should be made to measure the polarization and the anisotropy of the diffuse X-rays. The electron spectrum measurements and the measurements of a possible anisotropy and polarization of the diffuse X-rays will further clarify the relative contributions of the galactic synchrotron X-rays and metagalactic Compton X-rays.

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Figure Captions

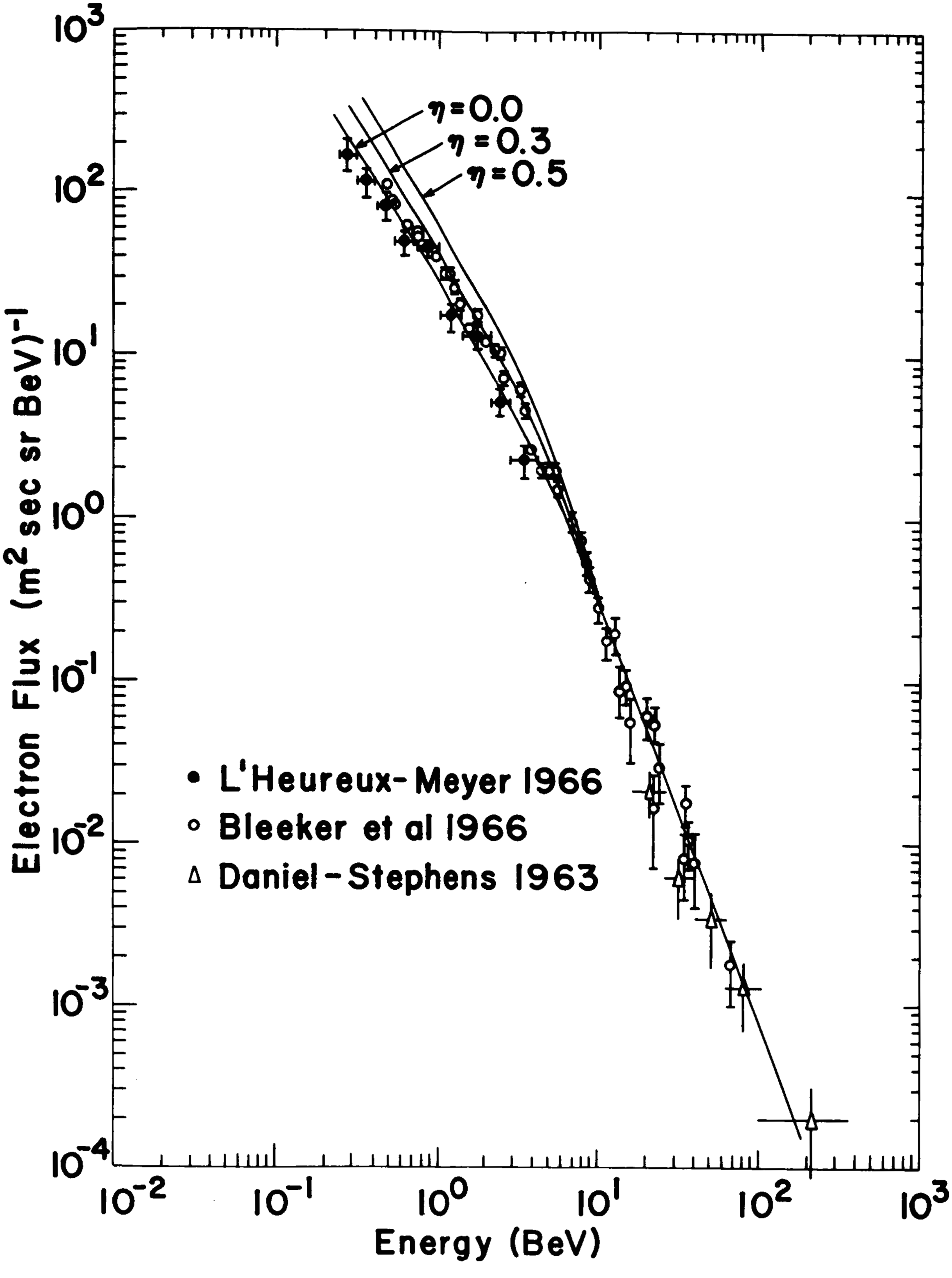
Fig. 1. The flux and energy spectrum of the primary electrons observed near solar minimum period (the years are the time of the experiment). Solid lines are the assumed equilibrium differential energy spectrum of electrons in the galactic halo for various degrees of residual modulation ($\eta = 0.0$, 0.3 and 0.5).

Fig. 2. Collected observations of sky brightness in the frequency range 10 - 10^4 MHz. Solid and open symbols represent measurements of the power received at various frequencies. *Solid circles:* Purton (1966); *open squares:* Turtle *et al.* (1962); *vertical bars:* Wielbinski and Yates (1965); *solid triangle vertex up:* Shain and Higgins (1954); *solid triangle vertex down:* Mills (1959); *open circle:* Howell and Shakeshaft (1966); *open triangle vertex up*: Roll and Wilkinson (1966); *open triangle vertex down:* Penzias and Wilson (1966). Dashed lines indicate the calculated flux and frequency spectrum of synchrotron radiation of relativistic electrons in galactic halo region for various values of η and $\langle H \rangle = 3\ \mu$ gauss. Dash-dot-dash lines represent similar calculations for $\langle H \rangle = 2\ \mu$gauss. Solid line represents the frequency spectrum of the assumed 3° K black body radiation.

Fig. 3. The flux and energy spectrum of diffuse X-rays. Solid and open symbols represent measurements of diffuse X-rays. *Open triangles:* Metzger *et al.* (1964); *open circles*: Bleeker *et al.* (1967a); *crosses:* Hayakawa *et al.* (1965); *open square*: Fisher *et al.* (1965); *X's:* Rothenflug *et al.* (1967); *solid bar:* Bowyer *et al.* (1964); *light bar:* Peterson (1965).

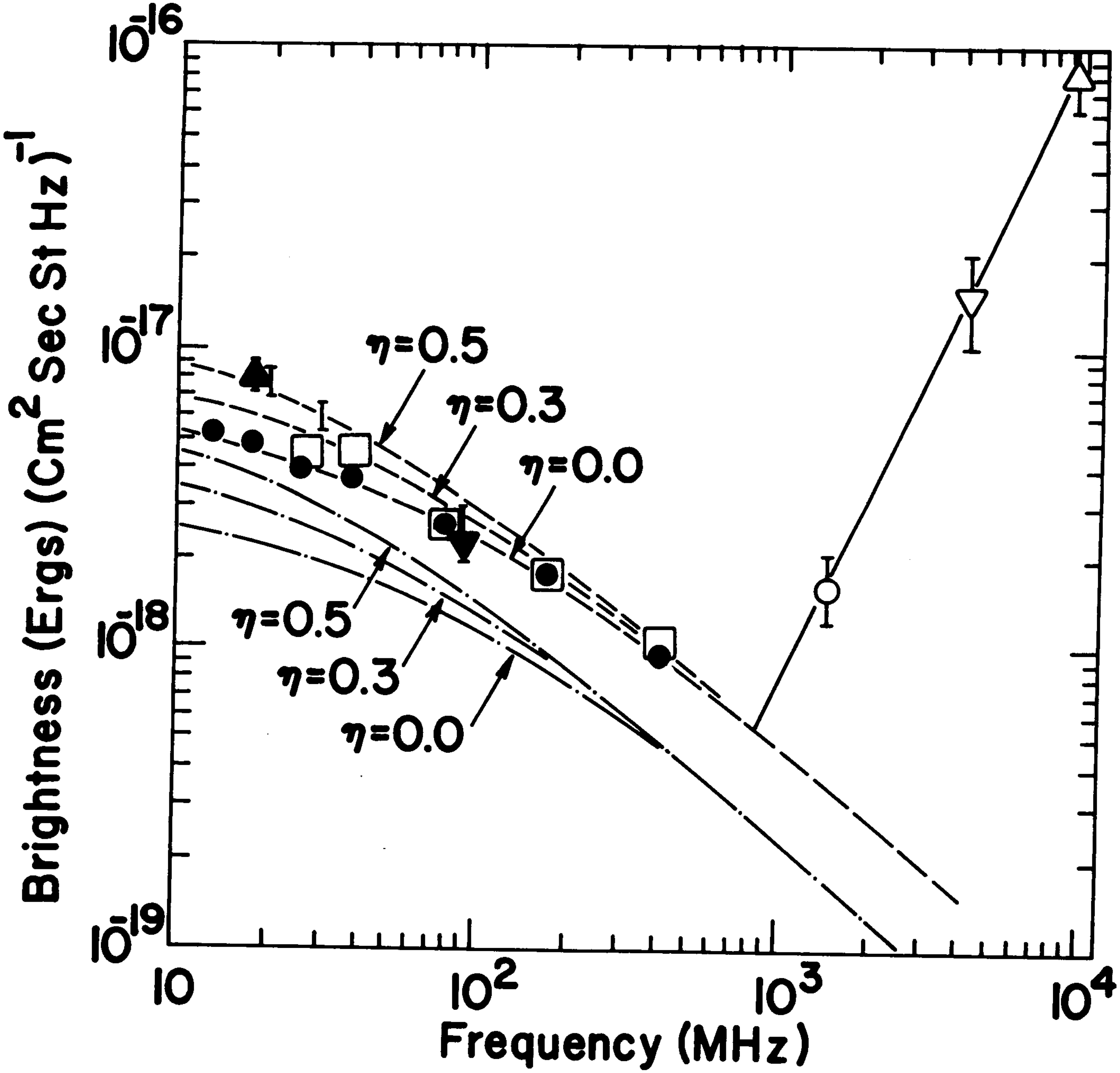
Dashed lines denote the calculated intensities of synchrotron X-rays emitted by the ultra high energy halo electrons, based on the assumed electron spectrum (dashed lines Fig. 4, γ = 2.6, 2.8 or 3.0). Dash-dot-dash line denotes the calculated spectrum of the metagalactic Compton X-rays produced by scattering of thermal photons with the assumed (see Fig. 4) extragalactic relativistic electrons. Solid line is the sum of synchrotron X-rays (for γ = 2.6) and metagalactic Compton X-rays. X-rays produced by inverse Compton scattering of galactic electrons (η = 0) with 3°K blackbody radiation is also shown.

Fig. 4. The measured differential energy spectrum of the primary electrons and its extrapolation to higher energies with negative exponent γ = 2.6, 2.8 and 3.0 in 10^{2} BeV to 10^{6} BeV. *Solid circle* represents the calculated value of electron flux based on air shower measurements of Gawin *et al.* (1965) and *diamond* represents similar value derived from the measurements of Toyoda *et al.* (1965). Dash-dot-dash line is the assumed energy spectrum of metagalactic electrons.



η = 0.0
η = 0.3
η = 0.5
● L'Heureux-Meyer 1966
○ Bleeker et al 1966
Δ Daniel-Stephens 1963
Electron Flux $(m^2\ \text{sec sr BeV})^{-1}$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
Energy (BeV)

Figure 1



10^{-16}
10^{-17}
10^{-18}
10^{-19}
Brightness (Ergs) (Cm^2 Sec St Hz)$^{-1}$
10
10^2
10^3
10^4
Frequency (MHz)
η=0.5
η=0.3
η=0.0
η=0.5
η=0.3
η=0.0

Figure 2

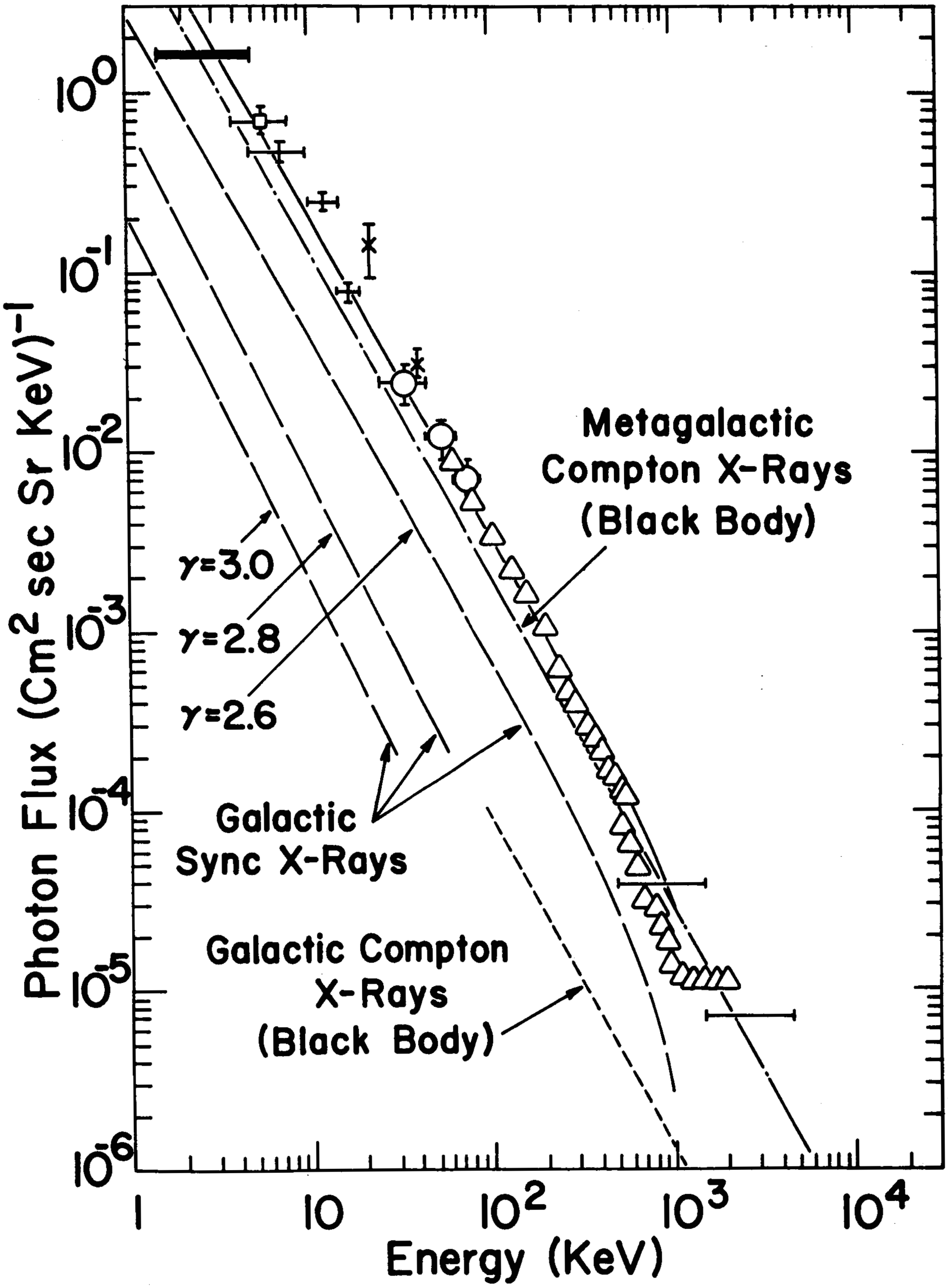

Photon Flux (Cm^2 sec Sr KeV)$^{-1}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
10^2
10^3
10^4
Energy (KeV)
Metagalactic
Compton X-Rays
(Black Body)
γ=3.0
γ=2.8
γ=2.6
Galactic
Sync X-Rays
Galactic Compton
X-Rays
(Black Body)

Figure 3

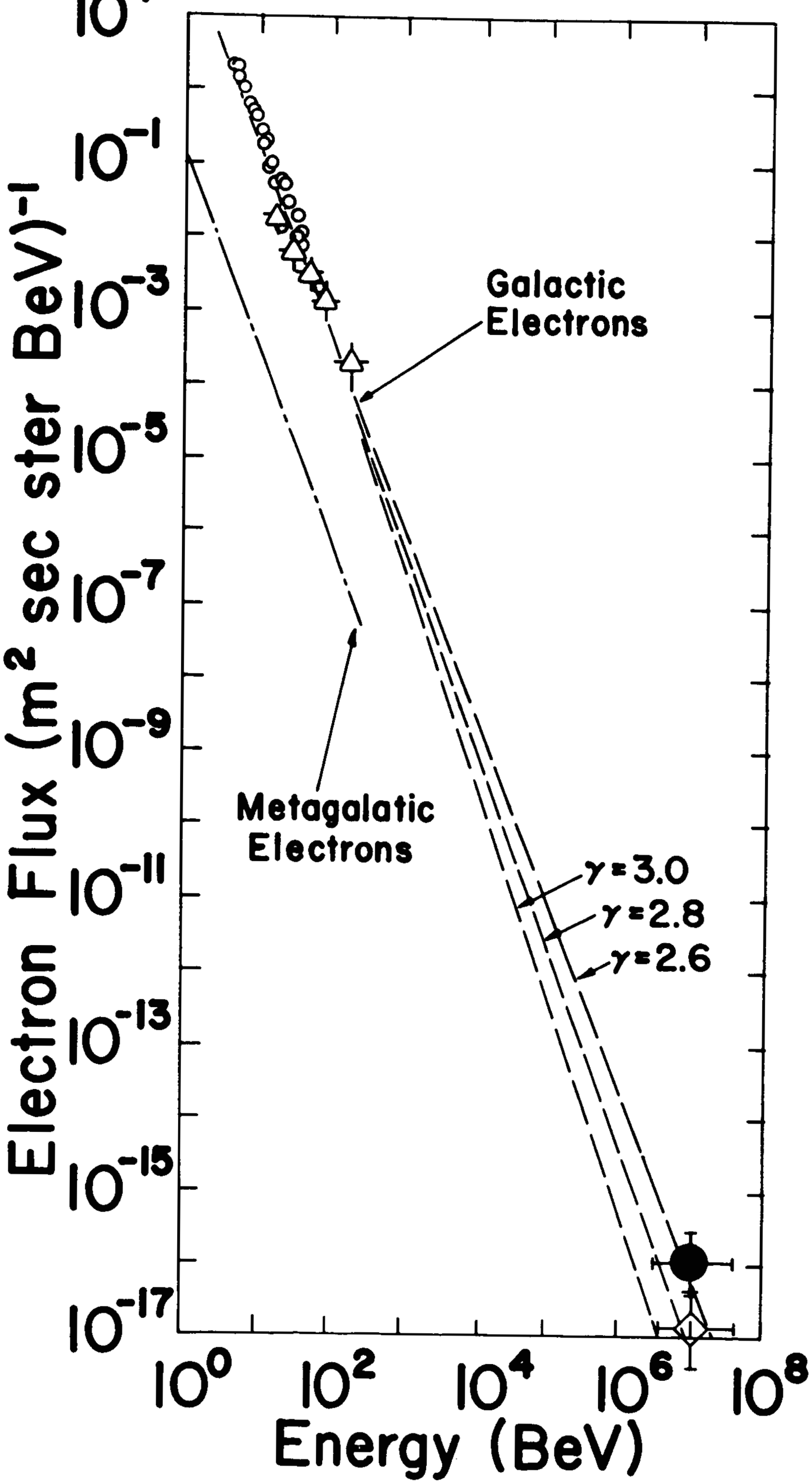

Electron Flux (m² sec ster BeV)⁻¹
10¹
10⁻¹
10⁻³
10⁻⁵
10⁻⁷
10⁻⁹
10⁻¹¹
10⁻¹³
10⁻¹⁵
10⁻¹⁷
Galactic Electrons
Metagalatic Electrons
γ=3.0
γ=2.8
γ=2.6
10⁰
10²
10⁴
10⁶
10⁸
Energy (BeV)

Figure 4