PROTONS IN THE EARTH'S MAGNETIC FIELD*

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The identity, flux, and energy distribution of particles trapped in the earth's magnetic field have been determined for those particles which penetrate more than 6 g/cm^2 of material.

A small stack of nuclear emulsions has been exposed to the particles in the lower Van Allen radiation belt.[1] The stack consisted of 10 sheets of Ilford K.5 emulsion, $1\frac{3}{8}$ in. $\times 1\frac{3}{8}$ in. $\times 600$ μ, enclosed in a water-tight stainless steel box which was mounted on the instrument board $1\frac{3}{4}$ in. from the side wall of the nose cone of a Thor-Able ballistic missile. The normal to this wall was parallel to the plane of the emulsions.

The missile was launched from Cape Canaveral on April 7. It reached a maximum altitude of 1230 km and spent about 15 minutes above 1000 km between the latitudes of 20°N and 3°N. The nose cone was recovered in the South Atlantic and returned for analysis. The emulsions were in excellent condition.

The particles that penetrated 5 g/cm^2 of nose cone wall, 0.032 in. of stainless steel emulsion box, and a minimum of 1 mm of nuclear emulsion have been identified and their numbers and energies measured; these correspond to protons and electrons with energies greater than 75 Mev and 12 Mev, respectively. The separation of protons from electrons was done unambiguously for proton energies up to 700 Mev by measuring the ionization of their tracks, only. The background of π mesons and other particles that arose from trapped proton or cosmic-ray interactions in the walls of the nose cone was negligible. No attempt was made to determine the angular distribution of the charged particles in the belt because the nose cone of the missile was not oriented in space. Therefore, in all the results which follow, an isotropic distribution has been assumed.

All proton energies were measured using the g^* method of ionization.[2] Normalization was obtained for g^*'s from 5 to 7 using the tracks of protons which had residual ranges of 8 to 14 mm in the emulsions. The energies of these stopping protons were determined from their ranges. The scanning for tracks was done 5 mm in from the edge of the emulsion that was nearest the nose cone wall where accurate g^* measurements could be taken. In addition, scanning was done 1 mm from the edge to pick up low-energy protons which did not penetrate to 5 mm. All particles whose vertical angles were within $\pm 15°$ of the emulsion plane and whose horizontal angles, in the plane of the emulsion, were within $\pm 15°$ of the normal to the wall of the nose cone were accepted for measurement. The estimated absorber thickness in the backward direction was used to correct the proton spectrum for the number of protons which crossed the scan lines in the wrong direction. The calculated correction varied continuously from 10% at 75 Mev to 25% at 700 Mev. This was checked experimentally at 100 Mev.

Emulsions which underwent the same history as those exposed to the Van Allen belt except for being aboard the missile were scanned for background tracks. The proton background was small. After the background of tracks of plateau ionization was subtracted out, no electron signal remained. An upper limit of 1% is placed on the ratio of the number of electrons to protons that can penetrate 6 g/cm^2 of material.

The resulting value, N, the absolute number of protons Mev^{-1} sterad^{-1} sec^{-1} cm^{-2}, outside the nose cone at an altitude of about 1200 km is plotted versus the proton energy T in Fig. 1 on a log-log plot. The data approximate a straight line from the minimum detectable energy of 75 Mev to the maximum observed energy of 700 Mev. The data are represented by

$$N = N_1 T^{-n}, \tag{1}$$

where a least-squares fit to the data gives n=1.84 $\pm$ 0.08 and $N_1 = (2.1^{+1.0}_{-0.7}) \times 10^3$ protons Mev^{-1} sterad^{-1} sec^{-1} cm^{-2}. The data also fit an exponential

$$N = N_0 e^{-T/T_0}, \tag{2}$$

with $T_0 = 120 \pm 5$ Mev, and $N_0 = 0.84 \pm 0.07$ proton Mev^{-1} sterad^{-1} sec^{-1} cm^{-2}.

At least two theories have received considerable attention for the origin of the trapped particles in the earth's magnetic field: (1) Solar injection.[1] Since a solar origin would give protons of a few Mev, at most, it seems unable to account for the high-energy protons found in this experiment. (2) Earth neutron albedo. In this theory neutrons from cosmic-ray interactions in

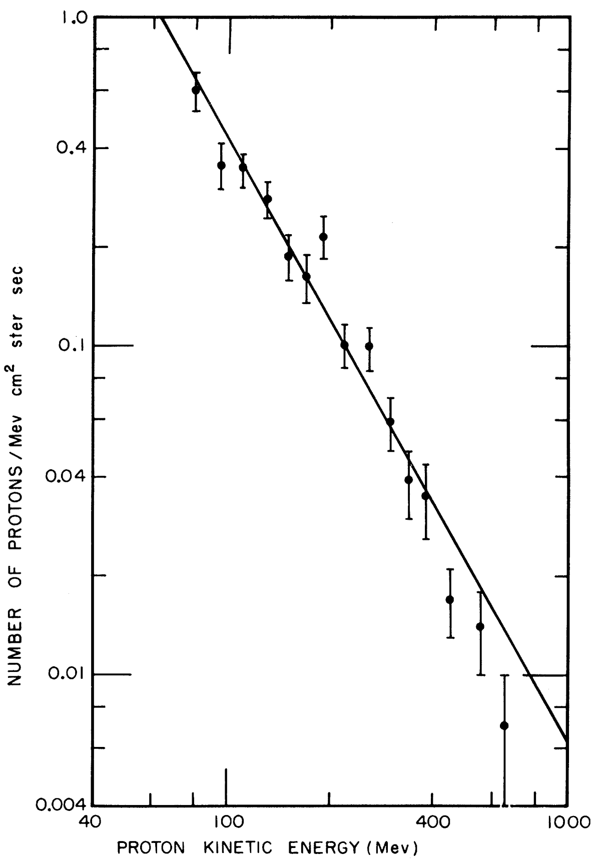

FIG. 1. The absolute energy spectrum of protons above 75 Mev in the lower Van Allen radiation belt at an altitude of 1200 km. The line is a least-squares fit of the equation $N = N_1 T^{-n}$ to the data and gives $N_1 = (2.1^{+1.0}_{-0.7}) \times 10^3$ protons Mev^{-1} sterad^{-1} sec^{-1} cm^{-2} and $n = 1.84 \pm 0.08$.

the upper atmosphere travel to the region of trapping and there decay into protons and electrons.[3-5] The earth neutron albedo can explain the data since high-energy neutrons are formed in cosmic-ray stars in the atmosphere in sufficient abundance to give the number of protons observed here.

Singer[2] predicted a velocity distribution that was proportional to $v^{-0.6}$. This distribution is transformed to give an energy distribution proportional to $T^{-0.8}$. Hess[6] made use of the neutron energy distribution that he measured high in the atmosphere to predict the neutron flux in the trapping region. From that he obtained a proton energy distribution proportional to $T^{-1.3}$ for $T_p \geq 100$ Mev (see the accompanying Letter). Neither of these distributions is as steep as the experimental data. If only the data for proton energies <300 Mev are used, $n = 1.56 \pm 0.12$ and $N_1 = (5.2^{+4.0}_{-2.3}) \times 10^2$ protons Mev^{-1} sterad^{-1} sec^{-1} cm^{-2}. This difference in n can be explained by the larger orbits and the subsequently greater loss of the high-energy protons.

The omnidirectional proton flux, J_{75}, i.e., the number of protons above 75 Mev which pass through a sphere of 1 cm^2 cross section per sec, is found by multiplying Eq. (1) by 4π and integrating over all proton energies greater than 75 Mev. The resulting value of J_{75} is 800 ± 200 protons cm^{-2} sec^{-1} If the power law with $n = 1.56$ is used to integrate down to a proton energy of 10 Mev, the resulting omnidirectional flux is 3×10^3 protons cm^{-2} sec^{-1} which is not in agreement with the value of 100 to 1000 that was obtained from previous data.[1] It appears that a still smaller value of n should be used at low energies. Better agreement with this previous result is obtained by using the exponential fit which gives an omnidirectional flux of 1100 protons cm^{-2} sec^{-1}

The radiation level at the position of the emulsion stack inside the nose cone due to electrons and electromagnetic radiation is less than 50 mr/hr. Using the exponential extrapolation of the proton data, the radiation level in space at 1200 km due to protons is estimated to be 1 r/hr.

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VAN ALLEN BELT PROTONS FROM COSMIC-RAY NEUTRON LEAKAGE

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One of the sources of particles for the Van Allen radiation belt is the decay of cosmic-ray neutrons leaking out of the atmosphere of the earth. Recently the cosmic-ray neutron energy spectrum has been measured,[1] and from this, by use of a multigroup neutron-diffusion calculation,[2] the neutron leakage has been calculated (Fig. 1). Some of the neutrons leaking out of the atmosphere decay in the earth's magnetic field and are trapped. From this leakage we can calculate the equilibrium proton energy spectrum in the inner Van Allen belt.

The calculated neutron leakage is given by $\phi(E) = 0.8E^{-2}$ neutron/cm² Mev sec in the region from 10 Mev to 1 Bev. The decay density of neutrons, dn/dV, is given approximately by

$$\frac{dn}{dV}(E,R) = \left[\frac{1}{v\gamma L}\exp\left(-\frac{R}{v\gamma L}\right)\right]$$

$$\times\,\phi(E)\left(\frac{R_e}{R}\right)^2 \text{ neutron decays/cm}^3 \text{ Mev sec,}$$

where L = neutron mean life, R_e = radius of earth, v = neutron velocity, R = distance from earth's center, and γ is the time-dilation factor. Protons resulting from neutron decays have very nearly the energy of the parent neutron. This gives us, for the proton source,

$$S(E) \cong k_1[\phi(E)/\beta\gamma].$$

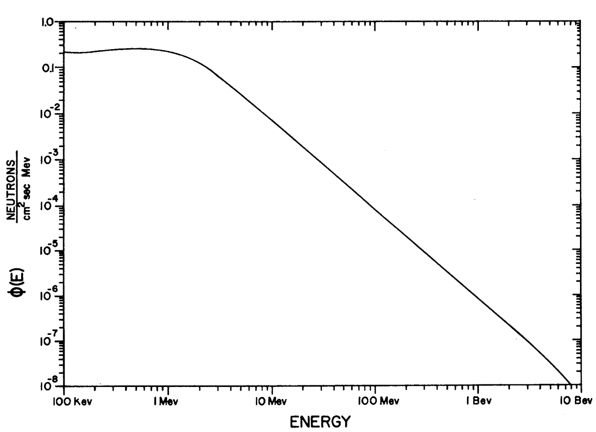

FIG. 1. The energy spectrum of the cosmic-ray neutrons that leak out of the atmosphere of the earth.

Whereas the loss mechanism for electrons in the Van Allen belt is multiple small-angle Coulomb scattering, the loss mechanism for protons is slowing down by collisions with bound electrons.[3]

In order to calculate the equilibrium proton energy spectrum we must consider the continuity equation for the slowing-down process. Following Singer[3] we can write

$$\frac{dN(E)}{dt} = S(E) - \frac{d}{dE}\left[N(E)\frac{dE}{dt}\right] = 0$$

for the steady state, where $N(E)$ is the equilibrium proton energy spectrum. This continuity equation follows the flow of protons along an energy axis. Now we can write $dE/dt = (dE/dx) \times (dx/dt) = (dE/dx)\beta c$; then, by substituting into the continuity equation, we get

$$\frac{k_1\phi(E)}{\beta\gamma} = \frac{d}{dE}\left[\left(k_2E^{-n}\right)\left(\beta c\frac{dE}{dx}\right)\right],$$

where we have taken $N(E) = k_2E^{-n}$. Approximating β, $\beta\gamma$, and dE/dx as functions of E, we can write[4]

$$\beta = 0.0885\, E^{0.344},$$

$$\beta\gamma = 0.0393\, E^{0.545},$$

$$dE/dx = 1.16\, E^{-0.586} \text{ Mev/cm of NTP air.}$$

These are all accurate to 5% or less in the energy region 80 Mev to 700 Mev. The continuity equation now becomes

$$k_3E^{-2.545} = \frac{d}{dE}\left[k_4E^{-n-0.242}\right] = k_5E^{-n-1.242}$$