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II-2-4. Injection of Trapped Protons from Solar Flare Particles

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Protons coming from the sun cannot be trapped directly. We calculate an injection mechanism as follows: Solar protons arriving at the polar cap produce albedo neutrons, some of which decay within the geomagnetic field at lower latitudes. In the decay, protons are released, most of which are dumped into the atmosphere at lower latitudes but some of which are trapped. We calculate the injection coefficients of these two cases as well as absolute intensities for typical solar events. The newly trapped protons show some peculiar properties when compared to the protons injected by the galactic cosmic rays. They exhibit a peculiar angle distribution and therefore spatial distribution with a depression of omnidirectional intensity in the equatorial plane. Their decay proceeds with the development of a peak in the energy spectrum which moves upward as time progresses.

Introduction

The occurrence of a large solar flare is sometimes followed by a series of violent geophysical disturbances. At least two of these disturbances may result in transient fluctuations in the trapped proton intensity. We refer to: (1) sudden variations in the atmospheric density (Jacchia,[1] 1960) and, (2) the injection of new protons. The first of these phenomena should produce detectable changes only at the inner edge of the belt where lifetimes are sufficiently short so as to be comparable with the time scale of the disturbance (say 1 day).

The possibility that solar protons contribute to the *trapped* proton population has been discussed by Armstrong, Harrison, Heckman, and Rosen[2] (1961) and by Naugle and Kniffen[3] (1961), and treated in some detail by Lenchek and Singer[4] (1962).

It is well known that charged particles coming from infinity cannot become strictly trapped in a dipole field without suffering some scattering or perturbation enroute. Hence solar protons either strike the earth or are turned back by the magnetic field after approaching to a certain minimum distance.

Low-energy protons spiraling into the polar atmosphere will generate neutrons. The decay of these additional neutrons within the proton belt will then inject new protons (Fig. 1). The source operates for a very short time (about a day) compared to the lifetimes of the resultant protons. We therefore have a phenomenon of impulsive proton injection followed by the decrease of this transient component, all superimposed on the steady proton component from the neutron albedo of galactic cosmic rays.

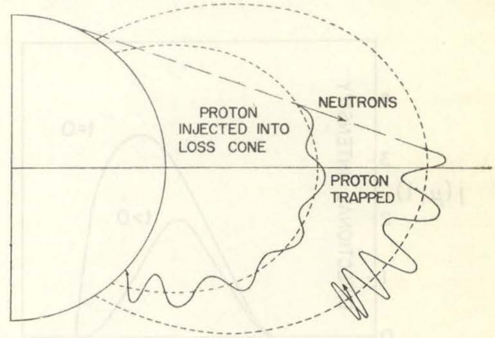

Fig. 1. Schematic to illustrate geometric considerations in trapping of protons from polar cap albedo neutrons. Note that most of the injected protons fall into the loss cone and do not survive. Note also the relatively inaccessible region at low altitudes above the equator.

Trapping of New Protons

Fig. 1 illustrates several important features of the polar albedo source. A "shadow" exists close to the equator so that for a source limited to latitudes greater than a given λ no injection takes place along lines of force which have equatorial distances $r_e < r_{min}(\lambda)$.

Although injection may take place on lines of force which lie higher than r_{min}, most of the injected protons fall into the loss cone and are not trapped. For lines of force extending to about two earth radii or less, the bulk of the injected protons simply spiral along the lines and plunge into the atmosphere. We therefore have, in effect, a mechanism for *transferring* low-energy charged particles from the polar cap, where they are above cutoff rigidity, to low latitudes where they are below cutoff rigidity.

Further examination of Fig. 1 reveals that the polar albedo component of the trapped protons will exhibit a peculiar angular distribution. Orbits with equatorial pitch angles α_e close to 90° cannot be populated by this mechanism. Fig. 2 is a schematic representation of the equatorial angular distribution to be expected. Since protons are negligibly deflected during their lifetime the time-

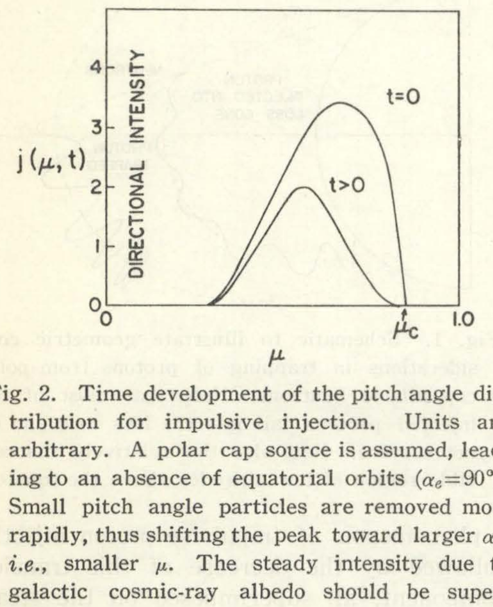

Fig. 2. Time development of the pitch angle distribution for impulsive injection. Units are arbitrary. A polar cap source is assumed, leading to an absence of equatorial orbits ($\alpha_e=90°$). Small pitch angle particles are removed most rapidly, thus shifting the peak toward larger α_e, *i.e.*, smaller μ. The steady intensity due to galactic cosmic-ray albedo should be superimposed.

development of the angular distribution is simply a decay of intensity at a rate proportional to the atmospheric density. Small pitch angle orbits see a larger atmospheric density so that the intensity in such orbits decays more rapidly than in orbits with larger values of α_e. The peak in the distribution therefore tends to shift toward larger equatorial pitch angles.

The spatial distribution of omnidirectional intensity of the polar albedo component will also differ markedly from that of the galactic

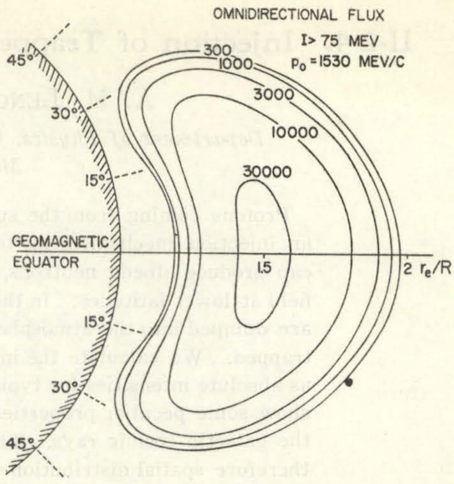

Fig. 3. Omnidirectional proton intensity >75 Mev computed on the basis of global neutron albedo. (Lenchek and Singer 1962).

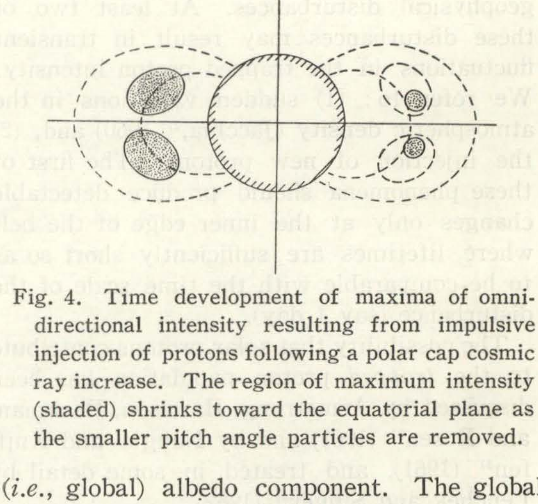

Fig. 4. Time development of maxima of omnidirectional intensity resulting from impulsive injection of protons following a polar cap cosmic ray increase. The region of maximum intensity (shaded) shrinks toward the equatorial plane as the smaller pitch angle particles are removed.

(*i.e.*, global) albedo component. The global albedo component exhibits a maximum intensity in the equatorial plane (Fig. 3). In contrast, the polar component should show a maximum omnidirectional intensity at high latitude and a depression at the equatorial plane (Fig. 4). This is a simple consequence of the peak in the angular distribution. As the peak in the angular distribution shifts toward $\alpha_e=\pi/2$, the location of the maximum omnidirectional intensity will shift toward the equatorial plane. This effect is illustrated schematically in Fig. 4.

Following the injection, the intensity decays at a rate determined chiefly by the atmospheric density and partly by the shape of the energy spectrum. The behavior of this transient component (which is superimposed upon the steady galactic albedo component) is described by the continuity equation

$$\frac{\partial n(E,t)}{\partial t}=-\frac{\partial}{\partial E}\left[n\frac{\partial E}{\partial t}\right] \quad (1)$$

assuming nuclear interactions are negligible in this energy range.

Equation (1) leads to a differential intensity $j(E,t)$ which is related to the initial intensity $j(E,0)$ by (Ray,[5] 1960)

$$j(E,t)=j(E,0)[1+\tau E^{-3/2}]^{-2(n+1)/3} \quad (2)$$

assuming $j(E,0)=\text{constant } E^{-n}$. Here

$$\tau=7.7\times10^{-12}\,\bar{\rho}_E t$$

for t in seconds and E in Mev. Here $\bar{\rho}_E$ is the number of free electrons in the atmosphere (exosphere), averaged over the spiral path. For orbits mirroring above 1000 km this quantity will typically be in the range $\sim10^3$ to $\sim10^6$ cm^{-3}.

An example of the decay of an initial power law spectrum is given in Fig. 5. We observe that a peak develops in the spectrum and the peak moves *upward* in energy. The time scale of the decay depends upon $\bar{\rho}_E$, which, in turn, depends on α_e. We may therefore view Fig. 5 as a representation of the energy spectra existing at *different* pitch angles but at the *same instant*, the lower curves corresponding to smaller pitch angles.

The lifetimes of these protons are on the order of months to years. This mechanism may therefore be the dominant source of trapped protons at $r_e \gtrsim 1.5\,R$ for $E<50$ Mev. However, it must be noted that these new protons are injected close to the outer edge of the proton belt where nonadiabatic effects

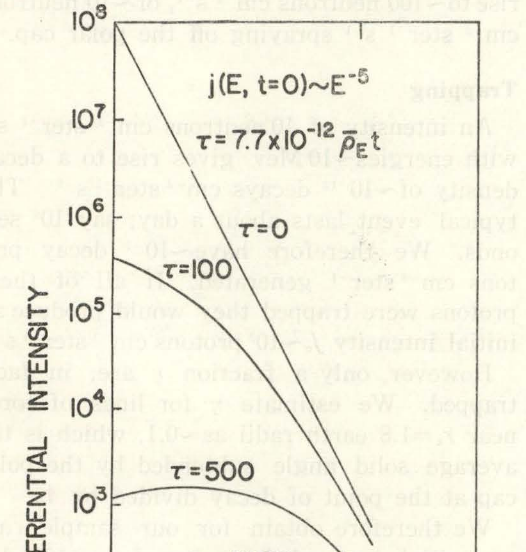

Fig. 5. Time development of energy spectrum for impulsive injection, assuming an initial spectrum E^{-5}. Note that the time scale of the phenomenon depends on the atmospheric density $\bar{\rho}_E$. For $\bar{\rho}_E\sim10^6$ the curve $\tau=500$ represents $\sim$2 years after injection.

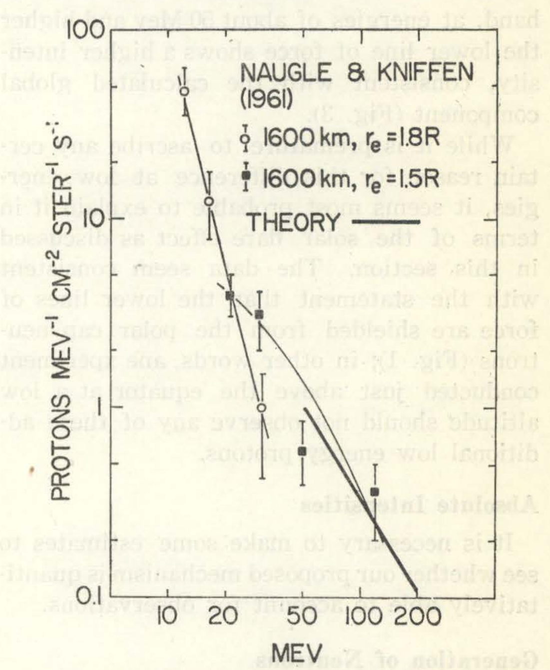

Fig. 6. The data points are results of a time-resolved nuclear emulsion flight (Naugle and Kniffen 1961) into the edge of the proton belt. The heavy solid curve is the equilibrium spectrum resulting from injection from global neutron albedo (Lenchek and Singer 1962). Both spectra refer to altitudes of 1600 km but the open circles refer to a line of force extending to 1.8 earth radii geocentric distance while the solid data points refer to a lower-lying force line which would be shielded from a polar cap source which was limited to latitude >52°.

become important. Therefore, the lifetimes set by energy loss are only *upper limits*.

Observation of Solar Flare Effects

No direct observations of trapped protons have been made immediately following a solar flare. However, the photographic emulsion experiments carried out by Naugle and Kniffen[3] (1961) yielded data showing a substantial difference in the energy spectrum depending on the line of force. The outer line of force reaching to $\sim 1.8\ R$ has a spectrum E^{-4} at energies below 50 Mev, while the spectrum taken along a line of force reaching to $\sim 1.5\ R$ is about $E^{-1.3}$. More importantly, the differential flux at about 10 Mev is higher by about an order of magnitude on the outer line of force (*cf.* Fig. 6). It may be still higher at lower proton energies which are inaccessible to observations. On the other hand, at energies of about 50 Mev and higher the lower line of force shows a higher intensity, consistent with the calculated global component (Fig. 3).

While it is premature to ascribe any certain reason for this difference at low energies, it seems most probable to explain it in terms of the solar flare effect as discussed in this section. The data seem consistent with the statement that the lower lines of force are shielded from the polar cap neutrons (Fig. 1); in other words, ane xperiment conducted just above the equator at a low altitude should not observe any of these additional low energy protons.

Absolute Intensities

It is necessary to make some estimates to see whether our proposed mechanism is quantitatively able to account for observations.

Generation of Neutrons

The low-energy solar protons impinge mostly near the poles. They are nearly isotropically distributed, so that most of the protons enter the atmosphere at large zenith angles. Hence they stop at high enough altitudes so as to enhance the probability of generating a neutron which is capable of escaping from the atmosphere. Neutrons with energies >10 Mev have scattering mean free paths in nitrogen $>15\ \mathrm{g\,cm^{-2}}$, while protons of <150 Mev have ranges $<15\ \mathrm{g\,cm^{-2}}$. Because the proton spectrum is so steep, the major contribution to the neutron production will be made by protons of less than this energy. Hence, almost all of the neutrons will be generated within a single scattering length of the top of the atmosphere. We may therefore assume that almost all upward moving neutrons escape.

A lower limit to the neutron yield when protons with $E \gtrsim 30$ Mev bombard nitrogen is provided by the observations of Tai *et al*[6] (1958). They find a yield W of 3.2×10^{-3} neutrons per proton for 32 Mev protons stopping in a thick target. Therefore, an event of the magnitude of the November 12-13, 1960, event, in which the proton intensity $>$ 32 Mev reached $3\times10^4\ \mathrm{cm^{-2}\ s^{-1}}$, (Ogilvie, Bryant and Davis[7], 1961; Lin[8] 1961) gives rise to ~ 100 neutrons $\mathrm{cm^{-2}\ s^{-1}}$, or ~ 10 neutrons $\mathrm{cm^{-2}\ ster^{-1}\ s^{-1}}$ spraying off the polar cap.

Trapping

An intensity of 10 neutrons $\mathrm{cm^{-2}\ ster^{-1}\ s^{-1}}$ with energies ~ 10 Mev gives rise to a decay density of $\sim 10^{-12}$ decays $\mathrm{cm^{-3}\ ster^{-1}\ s^{-1}}$. The typical event lasts about a day; say 10^5 seconds. We therefore have $\sim 10^{-7}$ decay protons $\mathrm{cm^{-3}\ ster^{-1}}$ generated. If all of these protons were trapped they would produce an initial intensity $J_o \sim 10^3$ protons $\mathrm{cm^{-2}\ ster^{-1}\ s^{-1}}$.

However, only a fraction η are, in fact, trapped. We estimate η for lines of force near $r_e=1.8$ earth radii as ~ 0.1, which is the average solid angle subtended by the polar cap at the point of decay divided by 4π.

We therefore obtain for our sample case an initial trapped intensity $J_o=\eta\times10^3=100$ protons $\mathrm{cm^{-2}\ ster^{-1}\ s^{-1}}$, with energies ~ 10 Mev. This is on the order of the intensity of the low energy component observed by Naugle and Kniffen.

If events of the magnitude of the February 23, 1956 or November 1960 events occur several times in each solar cycle of eleven years, their effect may *always* be observable (in varying stages of decay) in the form of distortions of the equilibrium spectrum. If such large events occur about once per year, then they are the dominant source of trapped protons with energy $\lesssim 50$ Mev at $r_e \gtrsim 1.5\ R_E$.

Intensity of Transferred Protons

We may also estimate the magnitude of

the transferred intensity by noting that continuity requires that the total number of non-trapped particles generated per second anywhere within a flux tube must flow out the base of the tube per second. If the directional integral intensity of neutrons is J_n cm^{-2} ster^{-1} s^{-1} then the total number of protons generated in a flux tube of unit area at the top of the atmosphere is

$$I' \sim (J_n \Lambda_n / \beta c) \times (\Omega) \times (V)$$

which is (the directional decay density)$\times$ (mean solid angle subtended by the source) $\times$(volume of the tube of force). (Since the trapping fraction is so small we assume all the decay protons fall within the loss cone and contribute to I'.) Here $\Lambda_n = 10^{-3}$ s^{-1} is the decay constant and βc is the velocity. Assuming, for illustration, $J_n = 10$ cm^{-2} ster^{-1} s^{-1}, Λ_n^{-1} $\beta c = 10^{13}$ cm, $\Omega = 1$ steradian and $V = 10^{10}$ cm^3 (corresponding to a flux tube intersecting the earth at$\sim$45°), we have $I' \sim 10^{-2}$ cm^{-2} s^{-1}. Thus, very great enhancement of the cosmic ray intensity in polar regions may be accompanied by a not insignificant enhancement in middle and low latitudes.

Acknowledgments

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Discussion

Dessler, A. J.: Can you give some ideas of the lifetime of trapped protons from polar cap neutrons which is implied by your parameter τ ?

Singer, S. F.: τ is equal to 7.7×10^{-12} $\bar{\rho}_B t$, where $\bar{\rho}_B$ is the average particle density integrated over the spiral orbit of the proton (See Lenchek and Singer, J.G.R. 1961).

Winckler, J. R.: The incidence of solar protons may move to latitudes below the polar region during the main phase of strong magnetic storms. In this case the secondary neutrons have angles more suitable for injection into the inner zone trapping region.

Singer: I agree with this comment.