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THE ROLE OF FAST RADIAL DIFFUSION IN THE FORMATION OF THE ENERGETIC ELECTRON POPULATION OF THE INNER BELT

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A large flux of greater than 100 *MeV* electrons was registered in the inner belt on low altitude satellites. The origin of the flux is discussed. It appears that slow radial diffusion ($D_0 = 10^{-13}$ s^{-1}) gives a low probability for penetration of these electrons to small *L* from the boundary of magnetosphere because of synchrotron radiation energy losses. It is found that they can enter into the inner belt region without such losses after great magnetic storms when fast radial diffusion sometimes takes place. Two great storms on 8-9 Feb., 1986 and March 24, 1991 are examples when one can directly observe a penetration of energetic electron fluxes into magnetosphere. The assumption about their Jovian origin is discussed.

Key words: Radiation inner belt; Electron flux; Radial diffusion; Synchrotron energy.

A IMPORTÂNCIA DA RÁPIDA DIFUSÃO RADIAL NA FORMAÇÃO DA POPULAÇÃO DE ELÉTRONS DE ALTA ENERGIA DO CINTURÃO INTERNO DE RADIAÇÃO - *Um grande fluxo de elétrons com energia superior a 100 MeV foi observado a bordo de satélite de órbita baixa no cinturão interno de radiação. A origem deste fluxo é discutida. Parece que a difusão radial com baixa velocidade ($D_0 = 10^{-13}$ s^{-1}) dá pouca possibilidade para explicar a penetração destes elétrons em baixos valores de L, proveniente da fronteira da magnetosfera, isto por causa da perda de energia dos mesmos por radiação sincrotron. Supõe-se que estes elétrons podem ser injetados no cinturão interno, nessa região, sem perder energia, após grandes tempestades magnéticas onde a difusão radial com alta velocidade é observada algumas vezes. Dois grandes eventos, em 8-9 Fevereiro 1986 e 24 Março 1991, mostram "in situ" a penetração de elétrons de alta energia na magnetosfera. A consideração de que estes elétrons também podem ser originários da atmosfera de Júpiter é aqui discutida.*

Palavras-chave: *Radiação do cinturão interno; Fluxo de elétrons; Difusão radial; Energia sincrotron.*

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INTRODUCTION

During the last 10 years, many measurements of the population of highly relativistic electrons (20-1000 *MeV*) trapped in the Earth's magnetosphere were made on board of low-altitude satellites (Just et al., 1983; Galper et al., 1983; Voronov et al., 1986). At least some of these electrons appear not to be secondary in origin, but are accelerated by a magnetospheric process. In Fig. 1 one can see the flux values measured on board the "Intercosmos-17" satellite (altitude - 500 km, inclination 82°, 1977-78) (Just et al., 1983). Two populations of electrons are evident in Fig. 1. The first has $H_{min} > 200$ km (trapped electrons), while the second one has $H_{min} < 200$ km (albedo). H_{min} is the minimum altitude of the mirror points of electrons drifting around the Earth. The fluxes are averaged over B value at a given L.

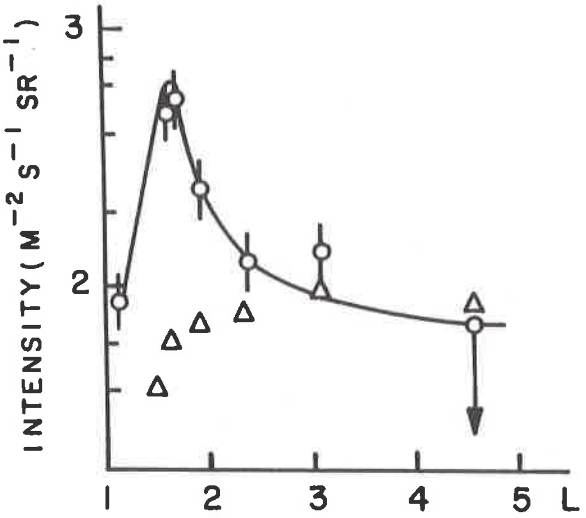

Figure 1. - The L - dependence of trapped (circles) and albedo (triangles) fluxes of electrons of > 100 *MeV*, measured at 500 km altitude.

Figura 1 *- A dependência L dos fluxos de elétrons aprisionados (círculos) e albedo (triângulos) de > 100 MeV, medidos a uma altitude de 500 km.*

Just et al. (1983) were the first to point out that trapped electrons can reach so high energies as > 100 *MeV* in the inner belt. The pitch-angle and L-distribution of these highly energetic electrons are presented in Galper et al., 1983, Voronov et al., 1986 and Dmitrenko et al., 1987.

These electrons may well be the most energetic magnetospheric particles which are accelerated in the magnetosphere. The most intriguing questions concerning these electrons are about their acceleration mechanism and the ultimate origin in the magnestosphere. There are two hypotheses of origin of these electrons in the low L region.

The first one supposes that they are the products of nuclear interactions of relativistic protons trapped in the inner belt with residual atmosphere (Gusev et al., 1984). It can explain the shape of the spectrum and gives the flux value close to the measured one. It predicts also the charge ratio (Ne^+/Ne^-) in the fluxes about 2.7. But the experimental value, measured with magnetic spectrometer, is (Ne^+ / Ne^-) = 0.3 (Voronov et al., 1986).

The second hypothesis (Dmitrenko et al., 1987) supposes that trapped high energy electrons come from outside of magnetosphere due to the process of common radial diffusion caused by positive fluctuations of the geomagnetic field. The particle energy in this case increases due to conservation of its magnetic moment. However the authors did not take into account that this process is very slow and takes dozen years. During this period the electrons must lose their energy by synchrotron radiation.

Let us calculate the value of synchrotron losses of electrons diffusing into the magnetosphere. The synchro-tron energy losses are given by the equation (Ginzburg, 1987):

$$dE / dt = 3.8 \cdot 10^{-6} B^2 E^2, GeV \cdot s^{-1}, \qquad (1)$$

where B is the magnetic field in gauss. For the equator we take $B = 0.312/L^3$.

Taking into account that during radial diffusion the electron energy changes as $L^{-3/2}$ and the rate of motion across L due to radial diffusion is $dL/dt = 12D_0L^9\ s^{-1}$ (Tverskoy, 1968), we obtain the next equation of changing of electron energy versus L:

$$dE / dL = -1.5E / L + 3.1 \cdot 10^{-8} E^2 L^{-15} / D_0, \qquad (2)$$

where the first term of the right hand describes the increase of electron energy during radial diffusion and the second one describes the decrease of electron energy due to synchrotron losses.

The solution of the equation is (see Fig. 2):

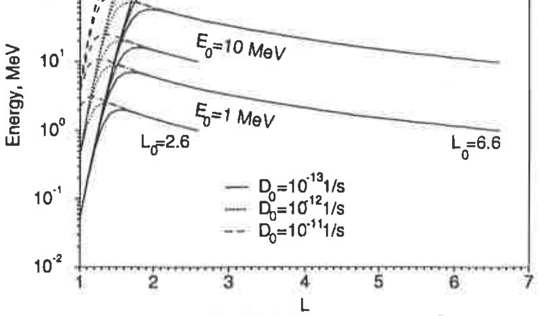

Figure 2 - Change of electron energy due to radial diffusion and synchrotron energy loss.

Figura 2 *- Mudança da energia de elétrons devido à difusão radial e perda de energia sincrotron.*

$$E(L) = \frac{5\cdot 10^8 D_0 L^{14}}{1-\left(\frac{L}{L_0}\right)^{15.5}\left(1-\frac{5\cdot 10^8 D_0 L_0^{14}}{E_0}\right)} GeV . \qquad (3)$$

Here E_o, L_o are respectively the initial energy and L-shell, from which the process of diffusion starts.

According to Eq. 3, particle energy on a given L-shell is limited for any E_o by $E_{max} = 5.10^8 D_o L^{14}$ *GEV*, for commonly used $D_o = 10^{-13}$ s^{-1}; E_{max} = 1 *MeV* at L=1.2. However, the measured flux of trapped electrons of E>100 *MeV* here is about 100 times higher than the albedo flux (Just et al., 1983).

So high energy electrons have low probability to populate the inner belt by radial diffusion process with $D_o \sim 10^{-13}$ s^{-1} and we need to research if a faster process can do it. The examples of such events are presented below.

FEBRUARY MAGNETIC STORM

The injection of subrelativistic electrons at L=3.05 was observed on board the "Cosmos - 1686" satellite (altitude 350 km, inclination 51.6°) during the February 1986 storm with D_{st}=-312 *nT* (Fig. 3). The sensor is a dE/dx-E telescope with collimator opening angle 20°, oriented to accept particles with pitch-angle ~90°. The time intervals were selected when the satellite crossed the geodetic equator near the same longitude 47°W. One can therefore see the time evolution of space distribution of electron fluxes. Strong peak of electron fluxes in the energy range (0.1 - 2 *MeV*) appeared in the gap between radiation belts at L=3.05 in February 8. They created something like a new trapped electron belt there. Before Feb. 8 (Feb. 1., see Fig. 3) there were no trapped electrons in this region.

The injection of energetic electrons occurred until 5 hours before the storm maximum. The L into which electrons have been injected is in agreement with Tverskaja (1986):

$$D_{st} = 27500/L^4 \ nT. \qquad (4)$$

D_{st} here corresponds to the storm maximum. It was not clear why this relationship works when the storm maximum is not reached. But now after analysis of the phenomenon of the March 21, 1991 great particle injection (Blake et al., 1992) it is obvious that the first reason of injection of particles is an appearance of positive impulse of magnetic field before magnetic storm. The impulse results from the interaction of bow shock with the Earth's magnetosphere after solar flare. It means that the magnitude of the positive impulse must be proportional to the D_{st} value. But this suggestion must be checked.

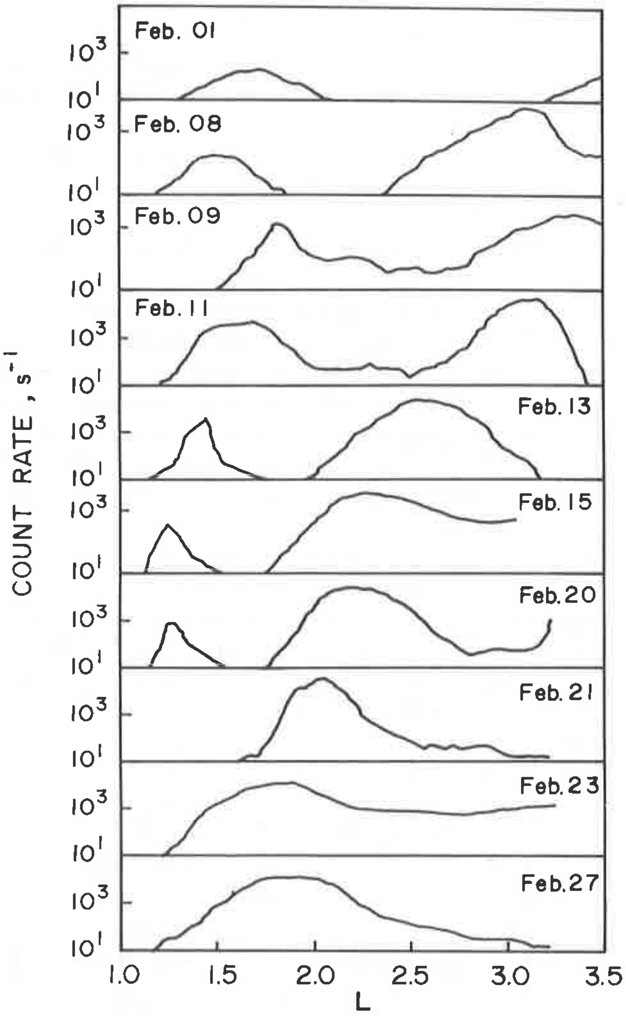

Figure 3 - The L-dependence of trapped electron fluxes in the range 0.6 - 0.9 *MeV* in February 1986.

Figura 3 - *A dependência L dos fluxos de elétrons aprisionados, na faixa de 0,6 - 0,9 MeV, em Fevereiro de 1986.*

The injection moves electrons only into the middle magnetosphere, but could not transport it to L < 2: until now L_{min} = 3.0 was observed (Tverskaja, 1986). But sometimes after a storm the conditions appear to allow more rapid radial diffusion.

In the same Fig. 3 one can see a phenomenon of fast penetration of injected electrons into the inner magnetosphere during 9, 13, 15, 20, 21, 23 of Feb. on the recovery phase of the storm. During those 2 weeks, a flux of injected electrons came into the inner belt region and, as a result, the inner belt flux was increased by an order of magnitude in comparison with the one of Feb. 20 and occupied L = 1.2-2.2.

If we assume that the radial diffusion is the process that moves electrons into magnetosphere then, using the results of Fig. 3 and relationship $D_{LL} = D_0 L^{10}$, we can get averages over 2 weeks $D_0 = 10^{-11}$ s^{-1}. The rate of diffusion is not constant and during some days the diffusion is more rapid. Our results show that the speed of the diffusion is not dependent on the electron energy in the range of 0.1 - 1 *MeV*. The derived D_0 is about two orders of magnitude higher than the commonly used one (10^{-13} s^{-1}).

For the first time the phenomenon of fast diffusion of electrons to *L*=1.3 due to magnetic disturbance caused by a solar flare was observed by Pfitzer & Winkler (1968) on OGO-3 satellite. In Fig. 4 (Pfitzer & Winkler, 1968) one can see the *L*-dependence of 0.29-0.69 *MeV* electron fluxes before and after the solar event of 2 Sept. 1966. The initial penetration of electron flux to *L*=2.2 took one day, the time of penetration to *L*=1.3 was about 30-40 days. After this period new and stable inner zone appeared. The penetration has been attributed by Blake et al., (1992) to radial diffusion that resulted from the injections farther out. After this observation and until the magnetic storm event of 8 Feb. 1986 the phenomenon was not observed and studied during 22 years. The phenomenon is important and of great interest for understanding of radiation belt origin, because it hints that all electron inner belt population (not only high energy one) is generated by the dramatic process of fast radial diffusion.

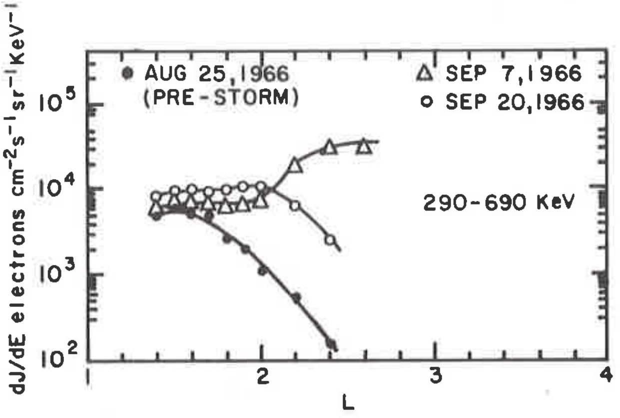

Figure 4 - The *L*-dependence of trapped electron fluxes in the range 0.29 - 0.69 *MeV* just before (25 Aug. 1966) and just after (7 and 20 of Sept., 1966) the solar event of 2 Sept., 1966 (Pfitzer & Winkler, 1968).

***Figura** 4 - A dependência L dos fluxos de elétrons aprisionados, na faixa de 0,29 - 0,69 MeV um pouco antes (25 de Agosto de 1966) e imediatamente após (7 e 20 de Setembro, 1966) o evento solar de 2 de Setembro de 1966 (Pfitzer & Winkler, 1968).*

Our observations have an advantage in comparison with the OGO-1,3 data due to a more detailed time history of events that reveal the dynamics of the phenomenon. During OGO-1,3 observations the Starfish electron fluxes were significant and did not permit to observe the inner belt dynamics so clearly as during the 1986 storm event. In Fig. 3 it is also seen the dynamics of inner belt fluxes during the recovery phase of the storm: the injected flux is moving to low *L* and the inner belt flux is pushed gradually to low *L*. The compression of the magnetosphere shifts the inner belt flux maximum from *L*=1.7 at 1 Feb. to *L*=1.5 at 8 Feb. At 9 Feb. the magnestosphere became decompressed and the maximum of inner belt fluxes was shifted in the opposite direction to *L*=1.8. From 9 to 20 of Feb., inner belt electrons diffuse to the low *L*. At 21 Feb. the old inner belt flux disappears, being thrown down to atmosphere and at 23 Feb. the new electron population of inner belt appears. The same history was observed for electrons at 0.1 - 1 *MeV*.

The example of Feb. 86 event shows that energetic electrons can penetrate quickly into the inner belt region after being injected in the beginning of the storm into the magnetosphere. As far as the lifetime of relativistic electrons at altitudes of several hundred kilometers is about 1 year, one or two such events per year as ones of 8 Feb. 1986 or 2 Sept. 1966 (Pfitzer & Winkler, 1968) would supply the inner zone with the energetic population. Probably, the whole inner belt electron population is generated by dramatic processes, but not gradual ones.

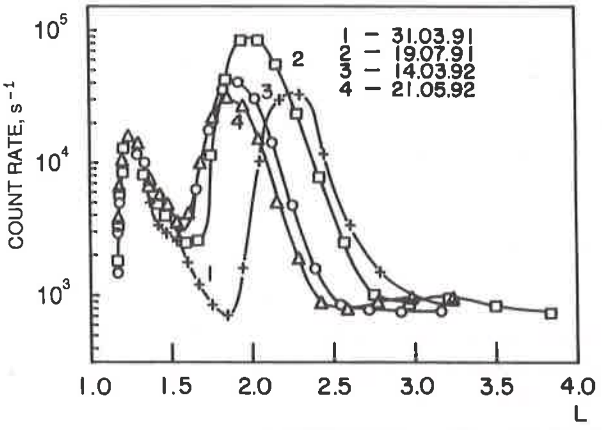

Figure 5 - The *L*-dependence of trapped electron flu-xes with energy > 8 *MeV* after the March 1991 event (Ginzburg et al., 1992).

***Figura** 5 - A dependência L dos fluxos de elétrons aprisionados, com energia > 8 MeV depois do evento de Março de 1991 (Ginzburg et al., 1992).*

MARCH 1991 STORM

The observations on board the Meteor (altitude 960 km, inclination 82°) and CRRES satellites during the storm at 24 March 1991 confirmed the assumption that after great storms high energy electrons can penetrate into the inner belt. The injection of electrons with *E* > 8 *MeV* was observed on board Meteor at 24 March 1991 at *L*=2.5 - 2.6 (see Fig. 5 kindly provided to us by Ginzburg et al., 1992) and at high altitudes on board CRRES (Blake et al., 1992) at the same *L*. At 31

March, one week after the storm maximum, a new high energy electron belt occupied L=2.1 - 2.3. If we try to describe this penetration phenomenon as a magnetic radial diffusion, then we get the coefficient $D_0=1.7.10^{-11}$ s^{-1}. Up to 21 May, 1992, the new belt was seen at L=1.85 and now the year averaged diffusion coefficient is equal to $1.3 \,.\, 10^{-12}$ s^{-1}. After 1.5 year the electron flux of the new belt entered into the inner belt and occupied a region on L=1.6 - 2.6 at an altitude of 960 km.

The similar process was seen at higher altitudes (B_0 / B =1.37) on board CRRES for electrons with E = 10 - 50 *MeV* (Blake et al., 1992). So one can see the penetration of high energy electrons into the inner belt *in situ*. It is interesting to note (Fig. 2) that electrons injected with the initial energies 1, 10, 100 *MeV* at L=2.6 also have limited energy at lower L because of synchrotron energy losses.

ENERGY BALANCE AND ORIGIN OF ELECTRONS

There are some reasons to suppose that relativistic electrons are injected into the magnetosphere from near geostationary L-shell. In fact, due to the first invariant conservation during injection and radial diffusion processes, electron energy is increased as $L^{-3/2}$. So if the electrons, which we observe at L=1.5 with E > 100 *MeV*, were injected (and transported into the inner belt) from L=6.6, their initial energy at initial L=6.6 was about 11 *MeV*.

According to Baker et al.(1986), large, persistent increases of high energy (3 - 10 *MeV*) electron fluxes frequently occur at geostationary L near solar minimum. So if they exist on L=6.6 at the moment of storm as it occurred at 8, 9 Feb. 1986 (Baker et al., 1986) they can be the source of the electrons injected to low L.

Baker et al. (1979) supposed that L=shells near L=6.6 are populated partly with Jovian electrons, so high energy electrons injected during great storms and transported in the inner belt can be of Jovian origin too. Thus, the whole high energy electron population in the magnetosphere, probably, have one source, - Jovian electrons. It is a rather surprising hypothesis but it can be the real one. To check this assumption one needs to compare the magnitudes and spectra of the injected electron fluxes with those at geostationary orbit. We can expect that during injection an electron spectrum must keep its slope due to conservation of magnetic momentum.

So we can conclude that the explanation of the high energy electron origin in the inner belt by fast radial diffusion after great storms seems to be possible. For proof we need to accumulated statistics of magnetic storms with electron injections and following penetration into inner magnetosphere to decide problem of balance the electron lifetime and frequency of injections.

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