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Anti-particles in the inner magnetosphere: energetic positron population

I. M. Martin, A.A. Gusev, G. I. Pugacheva and M. G. Silva Mello
Instituto de Física, Depto. de Raios Cósmicos e Cronología, Universidade de Campinas, Campinas, SP, Brasil.

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RESUMEN

Se analiza la generación de antipartículas atrapadas en el cinturón interior de la magnetosfera. Dichas partículas podrían tener flujos en exceso de los flujos interestelares generados por rayos cósmicos. Al considerar la existencia de un cinturón natural de positrones en la magnetosfera, proponemos que dichos positrones serían generados por una reacción nuclear de los protones relativistas atrapados en el cinturón anterior con la atmósfera residual. El espectro calculado de positrones a 10-100 *MeV* en el nivel superior $L = 1.2$ concuerda con los resultados experimentales.

PALABRAS CLAVE: Positrones, magnetosfera, Cinturón de Van Allen.

ABSTRACT

Anti-particles can be generated as secondaries by nuclear reactions of cosmic rays and energetic trapped particles with the residual terrestrial atmosphere, and can be trapped in the magnetosphere by the Earth's magnetic field. The trapped fluxes of anti-protons and positrons could be larger than the interstellar fluxes generated by cosmic rays. The possible existence of a natural positron belt in the Earth's magnetosphere is considered. It is suggested that the positrons may be produced by the nuclear reaction of trapped relativistic protons in the inner zone with the residual atmosphere. The positron spectrum in the range of 10 - 100 *MeV* at the top of $L = 1.2$ is calculated and found to be in agreement with experimental results.

KEY WORDS: Positrons, magnetosphere, Val Allen Belts.

INTRODUCTION

The Van Allen belts were discovered more than 30 years ago but their composition, source and formation mechanism are still a subject of discussion. Until recently it was not recognized that any appreciable amount of naturally occurring positrons is present in the Earth's inner radiation belt. However, recent data about energetic (several tens *MeV*) trapped electrons in the inner belt suggest that they might partially be explained as secondaries, resulting from interactions of trapped relativistic protons in the inner belt with the residual atmosphere (Gusev and Pugacheva, 1982; Galper *et al.*, 1983; Voronov *et al.*, 1986). It follows that an energetic positron population in this region is possible (Basilova *et al.*, 1982).

The basic mechanism of electron generation is the muon-electron decay of charged pions and kaons, resulting from the nuclear interaction of protons with an energy exceeding the reaction energy threshold of 390 *MeV*. As the trapped protons have a sharply decreasing spectrum, the energy of most interacting protons is near the threshold where pion multiplicity is small. Thus charge conservation favors mostly a positive pion production that results in an excess of positrons over negatrons.

In this paper a mechanism of formation of an energetic positron population in the inner zone is proposed and the positron spectrum is calculated at the top of the magnetic line $L = 1.2$, where the relativistic trapped proton intensity is at a maximum.

THE CONTINUITY EQUATION

High energy (>tens *MeV*) electrons are generated in the atmosphere in a chain reaction initiated by nuclear interactions involving protons in the inner zone and nuclei of atoms of the air constituents. The main mechanisms of electron generation are

(1) decay of short-lived particles:

$$\pi^{\pm}, K^{\pm} \Rightarrow \mu^{\pm} + \nu \qquad (1)$$

$$\mu^{\pm} \Rightarrow e^{\pm} + \tilde{\nu} + \nu \;; \qquad (2)$$

(2) conversion of γ quanta from neutral pion decay:

$$\pi^{\circ} \Rightarrow 2\gamma \rightarrow 2e^{+} + 2e^{-} \;; \qquad (3)$$

(3) internal conversion

$$\pi^{\circ} \Rightarrow 2e^{+} + 2e^{-} \;; \qquad (4)$$

(4) nuclear and electromagnetic cascades developed by particles in the atmosphere.

The contribution of each mechanism to electron flux (and to production spectrum) depends upon the atmospheric depth. At depths less than the proton nuclear range in the air, electrons are generated in the first interaction between proton and atoms of air constituents. At atmospheric depths exceeding the nuclear range, the electron flux includes second, third and higher generations of a nuclear cascade.

In the simple case of a stationary flux moving downwards through the rare atmosphere, the electron flux with energy E at a detection point at depth X g/cm^2 of a residual atmosphere is the sum of all electrons with the same direction at a distance X' above the detection point with energy E', such that the energy becomes equal to E after traversing a thickness X'. Then the electron flux for energy E at depth X is given by the particle conservation law:

$$F(E,X)=\int_{o}^{X} P_e(E',X')(dE'/dE)dX' \quad , \qquad (5)$$

where $P_e(E',X')$ is the production spectrum of electrons generated in 1 g/cm^2 of air. Taking into account ionization and radiation energy losses, the values of E, E', X and X' are related as

$$X'/X_0=\ln\left[(a+E'/X_0)/(a+E/X_0)\right] \quad , \qquad (6)$$

where $a=(dE/dX)_{ion}=0.002$ $GeVg^{-1}$ cm^2 is the electron ionization power in the air and $X_0=36$ $g\cdot cm^{-2}$ is the radiation length unit in the air, i.e. $(dE/dZ)_{rad}=E/X_0$. Equation (5) is applicable to the curvilinear path of an electron in the geomagnetic field, if X' is the amount of matter along the path from the generation to the detection point. Due to the decaying production spectra, the main contribution to the electron flux of a given energy comes from the 2 - 3 radiation lengths of air along the path.

At altitudes of 500-800 km where the density of the residual atmosphere is very low, electrons can be generated mainly in the first interaction of a trapped proton with atoms of air constituents through mechanisms (1,2). The charged pions and muons will decay in the residual atmosphere before they can interact with matter, due to their short half-lives. Of all electrons and positrons created by muon decay, only those with pitch-angles about 90° become trapped. Those with smaller pitch-angles are absorbed in the atmosphere. Thus we may consider only charged pions produced in the direction of the incident proton velocity, which simplifies the calculations.

The production spectrum of downward moving electrons from charged pions generated in the residual atmosphere can be obtained from (Daniel and Stephens, 1974):

$$P_e(E,X)=\frac{Q(E/q_1q_2)U_\pi U_\mu}{q_1q_2(U_\pi+E/q_1q_2)(U_\mu+E/q_2)} \quad . \qquad (7)$$

Here $U_\pi=H_0m_\pi/\tau_\pi c$; $U_\mu=H_0m_\mu/\tau_\mu c$; m_π, m_μ are the rest masses and τ_π, τ_μ the half-lives of charged pions and muons; H_0 is the standard atmosphere height; $q_1=0.8$ is the mean fraction of the energy carried away by a muon in a decay of a charged pion; $q_2=0.33$ is the same for electrons in muon decay, and $Q(E/q_1q_2)$ is the charged pion production spectrum.

At the top of the magnetic line $L=1.2$, H_0 is about 100 km and the terms E/q_1q_2 and E/q_2 in equation (7) can be neglected for electrons within the energy range 10 - 1000 MeV. Thus the equation is simplified to

$$P_e(E,X)=Q(E/q_1q_2)/q_1q_2 \quad , \qquad (8)$$

and the electron production spectrum is independent of atmospheric depth for altitudes of several hundred kilometers, and is determined only by the nuclear reaction of primary protons with the air target.

From (6) and (8), the integration in (5) over the amount of matter X can be replaced by integration over the electron energy. Hence the flux of trapped electrons is

$$F(E)=\int_{o}^{\infty} P_e(E')\cdot dE'/dE\cdot=\frac{P(>E)}{dE/dX} \quad . \qquad (9)$$

In order to calculate the pion production spectrum we use the double differential cross section (DDC) approximation and the numerical values of the intranuclear cascade model (Barashenkov and Toneev, 1972; Sobolevsky *et al.*, 1994). The generation probability of a pion with energy T and angle θ between the velocity vectors of the generated pion and the parent proton is aproximated by DDC:

$$\frac{d^2N}{dTd\omega}=n_\pi(E)\cdot T_0^{-1}\exp(-T/T_o)\cdot K(E,T)\exp(-T\theta/\tau(E)), \qquad (10)$$

where $n_\pi(E)$ is the pion multiplicity; $T_0^{-1}\exp(-T/T_0)$ is the spectrum of pions with mean energy T_o; $K(E,T)\exp(-T\theta/\tau(E))$ is the pion angular distribution normalized to 1, and ω is the solid angle.

The production spectrum of pions $Q(T)$ can be obtained as

$$Q(T)=\int_{\omega}\int_{Emin}^{Emax}(d^2N/d\omega dT)\cdot(dI/dE)\cdot(1/\lambda)d\omega dE. \qquad (11)$$

Here λ is the proton mean-free-path length, dI/dE is the differential spectrum of trapped protons, E_{max} is the maximum energy of the trapped protons and $E_{min}=390$ MeV. Table 1 shows the trapped proton integral flux at the top of $L=1.2$ (Vette *et al.*, 1978).

Table 1

Ep, MeV	100	200	300	400	600	1000
$Flux, m^{-2}s^{-1}$	$2.1\cdot10^7$	$9.3\cdot10^6$	$4.1\cdot10^6$	$1.8\cdot10^6$	10^6	$3\cdot10^5$

Since the pions are of sufficiently high energies, the angular distribution of electrons and muons is not taken into account. It is assumed that pions, muons and electrons have velocities in the same direction.

Trapped protons at the top of $L = 1.2$ are located in a narrow solid angle (about ~10° near pitch-angle 90°). Thus only pions with velocity vectors parallel to that of a parent proton (with an accuracy of 10°) produce electrons which can be trapped.

Table 2 shows the differential production spectra of positive and negative pions with velocity vectors parallel to the direction of proton velocity, as numerically calculated by means of the above procedure.

Table 2

Pion energy *MeV*	$Q\pi-$	$Q\pi+$
	$m^{-2}s^{-1}sr^{-1}GeV^{-1}g^{-1}cm^2$	
0 - 20	556.4	760.5
20 - 40	750.6	1177.3
40 - 60	846.9	1359.3
60 - 80	763.7	1408.1
80 - 100	635.2	1072.7
100 - 200	411.4	1103.8
200 - 400	522.1	1596.5
400 - 600	172.6	540.1
600 - 800	70.0	301.2
800 - 1000	20.0	79.0

Thus the electron half-life at the top of $L = 1.2$ is long enough to cause us to take into account in (9) ionization and radiation losses, as well as synchrotron radiation energy losses. Using the equation for synchrotron energy losses (Ginzburg, 1987):

$$dE/dt = 3.86 \cdot 10^{-6} E^2 B^2,\ GeV sec^{-1}\ , \qquad (12)$$

and for a mean atmospheric density ρ along the electron drift path we get

$$dE/dx = 3.86 \cdot 10^{-6} E^2 B^2/\rho c,\ GeV \cdot g^{-1} cm^2\ , \qquad (13)$$

where E and B are given in GeV and $Gauss$ respectively. The total energy losses are

$$dE/dx = 0.002 + 0.028E + 3.86 \cdot 10^{-6} E^2 B^2/\rho c\ \ GeV \cdot g^{-1} cm^2\ . \qquad (14)$$

The first and second terms are ionization and radiation losses in the air. At the top magnetic line $L = 1.2$ $B = 0.312/L^3 = 0.18$ Gauss, $\rho = 10^{-18}$ gcm^{-2} and for electrons with energy 30 MeV we obtain $(dE/dx)_{\text{synchr}} \approx (dE/dx)_{\text{ion+rad}}$. The more energetic the positrons the higher are the synchrotron losses. For the assumed mechanism of energetic positron flux formation, the synchrotron radiation losses are negligible only for the first closed L-shells (1.12-1.15), where the atmospheric density is much higher.

When synchrotron losses are dominant, the positron flux becomes proportional to the atmospheric density ρ (9,14):

$$F(E) = \frac{P(>E)}{dE/dX} \sim P(>E) \cdot \rho \qquad (15)$$

which decreases sharply with distance from the Earth's surface.

DISCUSSION

Figure 1 presents the results of the numerical calculations of integral intensity of trapped positrons at L=1.2 using Table 2 and equations (8-14) with and without synchrotron losses. Also, the total (positive and negative) pion production spectrum is shown.

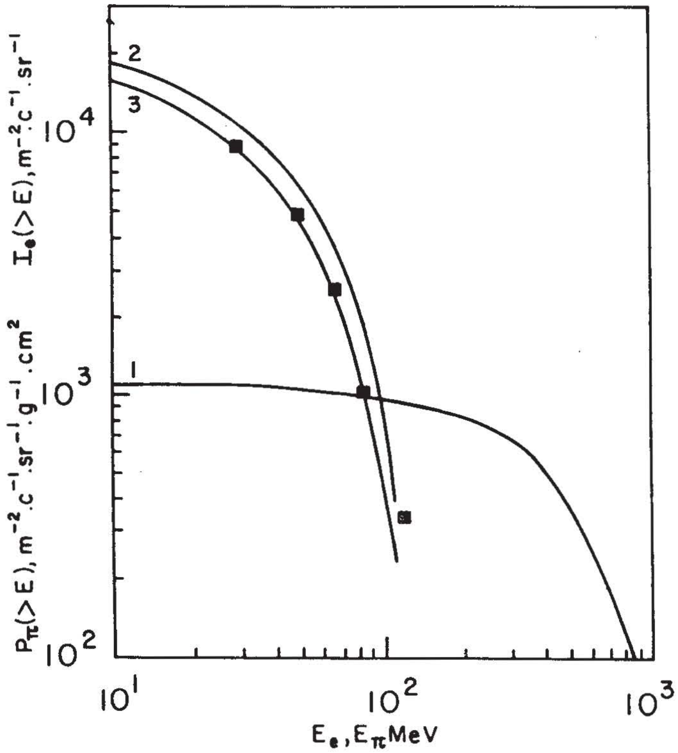

Fig. 1. Computed integral spectra at the top of L=1.2: 1- Positive and negative pion production $P_\pi(>E)$; 2- Positron flux without synchrotron radiation losses I_{e+} (>E); 3- Positron flux with consideration of synchrotron radiation losses I_{e+} (>E); solid squares- positron flux measured by COSMOS-1669, normalized to spectrum 3 at an energy of 30 *MeV*.

The calculated trapped positron flux at $E > 20$ MeV and $L = 1.2$ is about 10^4 m^{-2} s^{-1} sr^{-1} which is more than one order of magnitude higher than the albedo positron flux (~200 m^{-2} s^{-1} sr^{-1}) measured in the same L-shell by Koldashev (1986). Comparing this result with the computed trapped electron flux we obtain a charge ratio of trapped positron and electron fluxes for electron energies greater than 20 MeV (N_{e+}/N_{e-}) by a factor of about 2.7. The real ratio may be smaller due to possible additional sources of electrons, e.g. by radial diffusion into the magnetosphere.

Measurements of the trapped positron spectrum at $L = 1.2$ on board COSMOS-1669 (altitude ~400 km, inclination 51.6°) obtained by Koldashev (1986) are also shown in Figure 1. The positron spectrum within the range of 20 - 140 *MeV* was measured at the foot of the magnetic line at $L = 1.2 - 1.3$. The absolute value of the measured trapped positron flux with energy more than 20 *MeV* was found to be 920 ±200 positrons $/m^{-2}\ s^{-1}\ sr^{-1}$. In Figure 1 the data are normalized to a calculated positron flux of $E = 30$ *MeV*. The computed and measured positron spectra are in good agreement. The absolute values differ by a factor of 10, due to the difference in parent proton intensity at the top and at the foot of the magnetic field line on $L = 1.2$. According to Vette *et al.* (1978), they differ by the same factor for this value of L.

Another measurement of positron fluxes was performed on board MIR station (Galper *et al.*, 1993), and no excess of trapped over albedo positron flux was observed. But this result was for a wide range of $L = 1.1 - 1.6$ for positron belt observations. The positron belt, if it exists, should be expected to occur at $L \sim 1.2 \pm 0.1$. Thus a narrower range (around $L = 1.2$) should be more favorable for positron flux observations.

In the recent SAMPEX observations, energetic (> 15 *MeV/nuc*) deuterium and helium isotopes were detected at $L \sim 1.2$ (Cummings *et al.*, 1994; Looper *et al.*, 1994). The observations were also explained in terms of nuclear reactions of energetic trapped protons with the residual atmosphere. To produce energetic isotopes in a nuclear reaction, protons with an energy of about 200 - 300 *MeV* are required. This confirms our hypothesis that this source is powerful enough to produce secondary trapped particles.

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I.M. Martin, A.A. Gusev, G.I. Pugacheva and M.G. Silva Mello
Instituto de Física, Depto. de Raios Cósmicos e Cronología, Universidade de Campinas, C.P. 6165, 13083-970, Campinas, SP, Brasil.