NUMERICAL MODELLING OF THE PITCH–ANGLE SCATTERING AFFECT ON THE RADIATION BELT PROTONS DISTRIBUTION AT LOW ALTITUDES IN THE EARTH MAGNETOSPHERE

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Numerical simulation was carried out in the present paper to demonstrate the effect of the pitch-angle scattering on the phase space distribution of proton omnidirectional fluxes in the Earth magnetosphere. It was shown that for Mc'Ilvine parameter of order 2–4 even a small order of magnitude of the pitch-angle diffusion coefficient may essentially affects the phase space distribution of the radiation belt proton fluxes. It was also shown that for the purpose of the appropriate description of the protons behaviour at low altitude in the Earth magnetosphere the neutron albedo should be taken into account. Numerical modeling carried out clarifies that for the future predictions on the satellite measurements of proton distributions it is expedient to obtain the reliable theoretical pitch-angle quasilinear diffusion coefficients as well as to have the adequate physical model for the neutron albedo at low altitudes.

INTRODUCTION

Some problems of the protons radiation belt physics are still unsolved. The present report deals mainly with the modeling of the high-energy protons behaviour in the Earth magnetosphere taking into account the wave particle interaction and neutron albedo. This activity was invoked partially by the theoretical investigations [1] as well as the recent experimental observations. It was measured experimentally on board of SAMPEX [2] that the proton flux to the detector originally looked to the zenith observed to be equal after the board spinup to orientate the detector downward to the Earth. These experiments demonstrate that the important impact of the protons come from the "splash" energetic particle albedo. The theoretical problem of interest thus is the energy spectrum and altitude dependence of the neutrons produced by the cosmic ray albedo. At the same time it is obviously that the proton distribution in the radiation belt should be essentially affected by their interaction with the electromagnetic waves in the magnetosphere [3].

SIMULATION APPROACH

We start from the averaged Fokker-Planck equation for trapped protons distribution function in the Earth magnetosphere that will take into account stochastic distortion of the field lines, Coulomb scattering, wave-particle interaction as well as charge exchange with neutral atoms and the proton source due to neutron albedo. To formulate this problem we proceed from the Fokker-Planck type conservation equation in phase space

$$\frac{\partial f}{\partial t} = \frac{1}{\sqrt{g}}\frac{\partial}{\partial c_i}\sqrt{g}\left(d^i + D^{ij}\frac{\partial f}{\partial c_j}\right) + Q - S. \tag{1}$$

Here c_i are the constants of motion chosen as follows: c_1 is the proton magnetic moment, c_2 is the Mc'Ilvine parameter, defined as

$$c_2 = L = \frac{2\pi M}{R\Phi}, \tag{2}$$

where Φ is the magnetic flux through the proton drift trajectory, c_3 is the particle pitch-angle cosine at the equatorial mid plane.

The determinant of the metric tensor is

$$\sqrt{g} = c_3 \tau_b c_2^{-5/2}, \tag{3}$$

where τ_b is the bounce period of the proton drift motion. The value Q in Eq. (1) is the volume proton source due to the neutron albedo taken in the model form [4]

$$Q = Q_o(1-c_3^2)c_1^{-2}c_2^3 \exp(-\gamma c_1/\sqrt{1-c_3^2}), \tag{4}$$

where γ corresponds to [4] and Q_o is a parameter for investigation. The value S presents in Eq. (1) is the proton loss due to charge exchange process.

Following [5] we take the boundary conditions as a proton flux energy spectrum at $L = 7$ in the form

$$j = \varepsilon \left(e^{-\varepsilon/60} + 3.5 \cdot e^{-\varepsilon/10} + 100 \cdot e^{-\varepsilon/1.1}\right). \tag{5}$$

We set natural boundary conditions for all other boundaries in phase space.

METHOD USED

To carry out the numerical simulation of the high energy protons behaviour in the Earth magnetosphere we simplify Eq. (1) as follows.

We treat a steady-state proton distribution function, *i.e.*, $\dfrac{\partial f}{\partial t} = 0$. Coulomb collisions is taken into account as a slowing down process only

$$d^1 = 8.8 \cdot 10^{15} L^{9/2} c_1^{1/2} \begin{cases} 205 \left(\dfrac{L}{4.1}\right)^{-4.64}, & L < 4.1, \\ 13.0 \left(\dfrac{L}{4.1}\right)^{-4.64}, & L > 4.1. \end{cases} \tag{6}$$

Charge-exchange process of the neutral hydrogen with density n_{H_2} is considered in the "tau" approximation [5], with the effective process time τ_{cx}

$$\tau_{cx} = \sigma_\varepsilon \langle n_{H_2} \rangle. \tag{7}$$

Here < ... > denotes the bounce averaging over the proton drift trajectory,

$$\sigma_\varepsilon = \begin{cases} a_1 e^{-\varepsilon/\varepsilon_o}, & L < 2 \\ a_2 \varepsilon^{-\gamma}, & L > 2 \end{cases} \tag{8}$$

with $a_1 = 9.48 \cdot 10^{-16}$, $a_2 = 7.55 \cdot 10^{-23}$, $\varepsilon_o = 0.0275\,\mathrm{MeV}$, $\gamma = 5.64$ [7], and neutrals assumed to be distributed as follows

$$n_{H_2} = n_o \cdot H^\alpha, \quad n_o = 62544.2, \quad \alpha = -3.7. \tag{9}$$

Exp. (7) fits the experimental data presented in [8].

In our simulation the radial diffusion coefficient is taken in the form [1]

$$D^{22} = D_o L^{10}, \quad D_o = 3 \cdot 10^{-14} \tag{10}$$

that corresponds to the magnetic field stochastic distortion (it is suitable for the qualitative description presented here). Pitch-angle diffusion coefficient is taken in the model form [9]

$$D^{33} = \sigma \left(\frac{c_3}{c_{cone}}\right)^\delta \tag{11}$$

with $\sigma = 10^{-6}$ and $\delta = 1.5$ and pitch-angle cosine on the atmospheric loss cone

$$c_{cone} = \sqrt{1 - \frac{1}{L^3\sqrt{4 - 3/L}}}. \tag{12}$$

SIMULATION RESULTS

The numerical solution of Eq. (1) was made using the alternative direction implicit method for two cases, the first one is without the proton volume source, $Q = 0$, and the second one is with the model neutron albedo taken into account.

The model calculations with the proton flux equal to zero at the loss cone were carried out for the comparison with previous two-dimensional calculations in [8], where the pitch-angle scattering was omitted. The results of our calculations presented in Fig. 1a at least qualitatively reproduced that of [10]. Fig. 1b shows the calculated proton fluxes with proton distribution function equal to zero at the loss cone. From Fig. 1a and Fig. 1b one may see that for $L > 4$ the pitch-angle diffusion does not play the important role for protons distribution. On the other hand, for low values of L parameter the pitch-angle diffusion is significant and decries the omnidirectional proton flux more than to one-tenth of its former value.

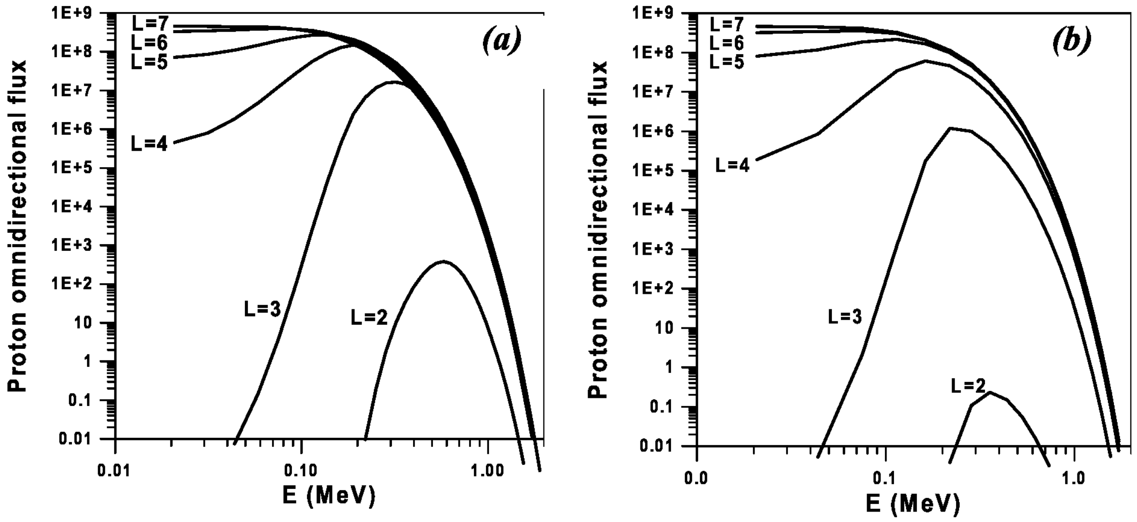

Figure 1: (a) proton flux versus energy for the model when atmospheric cone loss set to be absent; (b) atmospheric cone loss is taken into account

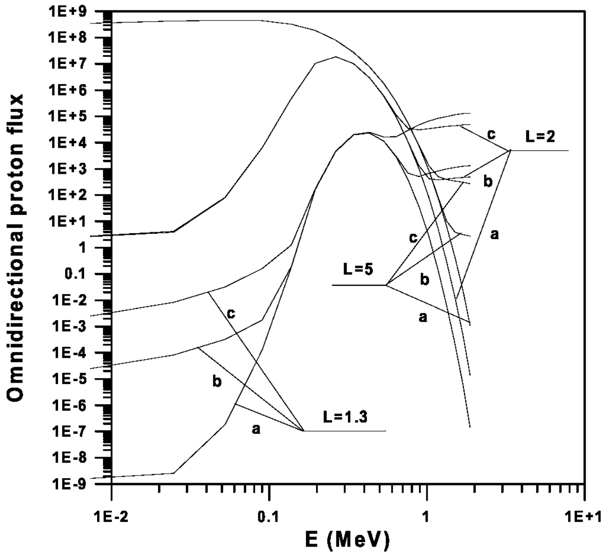

Figure 2: a) volume source is neglected; b) and c) volume source is taken into account, $Q_o(c)/Q_o(b) = 10^2$

Present calculations demonstrate that the pitch-angle scattering plays an important role for the proton flux distribution at low values of Mc'Ilvine parameter even without taking into account the volume source of protons. It should be pointed out that experimental observations show the higher level of the proton fluxes in the low energy region at low altitudes than the calculated ones. It may be explained with taking into account the neutron albedo in the numerical modeling. Numerical simulation results with the volume source in the model form of Eq. (4) are presented in Fig. 2. As the volume source amplitude is not well known, calculations were carried out for different source values. From Fig. 2 one may conclude that neutron albedo may be used to interpret the proton fluxes behaviour at low energies and low altitudes. At the same time, the energy spectrum of the volume source was taken in the model form. To carry out the comparative analysis of the calculation results and experimental observations this spectrum should be clarified.

CONCLUSIONS

The model and numerical calculations presented in the paper clarify the role of the pitch-angle scattering and neutron albedo for the proton distribution in the Earth plasmosphere. They demonstrate that even a small value of the pith-angle diffusion coefficient may strongly affect the proton distribution at least for small values of L and in the vicinity of the atmospheric loss cone. The modeling shows that neutron albedo may increase the proton omnidirectional flux at low energies and for low values of Mc'Ilvine parameter.

At the same time, the proposed approach was based on the assumption that proton distribution function is steady state. It is obviously that the time required for distribution function reaching to steady state is too long in comparison with the characteristic times of the solar wind variations. In this connection to obtain the reliable proton distribution function one should solve the nonstationary Fokker-Planck equation with taking into account the time variation of the proton source and Earth magnetic field geometry.

Proton volume source energy spectrum and altitude dependence affect essentially the proton fluxes, therefore, the theoretical investigations and comparison with experimental measurements are required to clarify the neutron albedo parameters.

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