Космічна наука і технологія. ДОДАТОК. 2001. Т 7. № 2. С. 15—18.

PITCH-ANGLE SCATTERING AFFECT ON THE RADIATION BELT PROTONS DISTRIBUTION

O. K. Cheremnykh[1], V. Ya. Goloborod'ko[2], S. N. Reznik[2]

[1]Space Research Institute, National Academy of Sciences of Ukraine
and National Space Agency of Ukraine, Kyiv, Ukraine

[2]Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv, Ukraine

Numerical simulation was carried out in the present paper to demonstrate the effect of the pitch-angle scattering on the phase space distribution of the proton fluxes measured 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 affect the phase space distribution of the radiation belt proton fluxes. Numerical simulations carried out demonstrate that for future predictions on the satellite measurements it is expedient to obtain the reliable theoretical pitch-angle quasilinear diffusion coefficients with the appropriate experimental verification.

INTRODUCTION

At present there are strong experimental evidences that protons are the main ion population of the Earth radiation belts that come from the Solar wind [1]. That is why it is important to investigate there behavior in the Earth magnetosphere. The Solar wind delivers protons to the Earth magnetosphere through two channels. The first one is a direct Solar wind protons trapping at the outer boundary of the magnetosphere confinement domain (i.e. the confinement domain of the ion drift motion in the Earth magnetosphere magnetic field). The second one is the proton source caused by the Solar wind neutrons albedo in the Earth magnetosphere. We will neglect this volume proton source because the experimental observations demonstrate that Solar protons come mainly from the Earth confinement domain boundary. Previous theoretical investigations as well as numerical simulations dealt only with the high energy proton flux distributions caused by the stochastic radial diffusion, charge exchange and slowing down by electrons [2]. Numerical simulation carried out in [3] was in qualitative agreement with the satellite measurements [3, 4] at least for high values of Mc'Ilvine parameter. At the same time, the latest experimental evidences [5] demonstrate that quasilinear pitch-angle diffusion should be taken into account to describe the measured Solar proton flux distribution over space and energy. This problem was treated numerically in [6] and at least qualitative agreement with the satellite measurements for the low-altitude trapped protons was obtained [7]. Now it is evident, that for the purpose of interpretation of the protons behavior in the whole Earth magnetosphere confinement domain one should take into account also the effect of quasiliniar pitch-angle scattering [8]. The latest theoretical investigation [9] shows that the main impact on the Solar protons pitch-angle diffusion occurs due to the interaction of particles with ion-cyclotron waves or whistlers [7]. At present this problem is still under consideration and we restrict our simulation with the model approach.

SIMULATION APPROACH

We start from the assumption that we may write 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. To formulate this problem we proceed from the Fokker—Planck type conservation equation in phase space.

$$\frac{\partial f}{\partial t} = \frac{1}{\sqrt{g}}\frac{\partial}{\partial c_{\mathrm{i}}}\sqrt{g}\left(d^{\mathrm{i}} + D^{\mathrm{ij}}\frac{\partial f}{\partial c_{\mathrm{j}}}\right). \tag{1}$$

This equation is written under the assumption that all processes are independent and random at the same time. This equation should be treated as an orbit averaging, i.e., as a drift Fokker—Planck equation. 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 (this variable may be recalculated to the real pitch-angle value by use of the approach proposed in [8].

The determinant of metric tensor is:

$$\sqrt{g} = c_3\tau_{\mathrm{b}}c_2^{-5/2} \tag{3}$$

where τ_{b} is the bounce period of the proton drift motion.

There is no volume proton source presented in this equation because, as it was pointed out earlier, we will neglect the neutron albedo. Following [10] we will take the boundary conditions as a proton flux energy spectra at $L = 7$ in the form

$$j = \varepsilon\left(\mathrm{e}^{-\varepsilon/60} + 3.5\mathrm{e}^{-\varepsilon/10} + 100\mathrm{e}^{-\varepsilon/1.1}\right). \tag{4}$$

This energy spectrum of the proton flux was reproduced from the satellite measurements and is in a good agreement with that of obtained by use of the experimental data interpolation package EP6 for the quiet Earth magnetosphere [12].

METHOD USED

To carry out the numerical simulation of the high energy protons behavior in the Earth magnetosphere we simplify Equation (1) in the following way.

We'll treat a steady-state proton distribution function , i.e., $\partial f/\partial t = 0$. Coulomb collisions will be taken into account only as a slowing down process [7]

$$d^1 = 8.8\cdot10^{15}L^{9/2}c_1^{1/2}\begin{cases}205\left(\dfrac{L}{4.1}\right)^{-4.64}, & L < 4.1,\\ 13.0\left(\dfrac{L}{4.1}\right)^{-4.64}, & L > 4.1.\end{cases} \tag{5}$$

Charge-exchange process on the neutral hydrogen with density n_{H_2} is considered in «BGK» approximation [4], with the effective process time τ_{cx}

$$\tau_{\mathrm{cx}} = \sigma_\varepsilon\langle n_{\mathrm{H}_2}\rangle, \tag{6}$$

here bracket $\langle\ldots\rangle$ denotes the bounce averaging over the proton drift trajectory,

$$\sigma_\varepsilon = \begin{cases}a_1 e^{-\varepsilon/\varepsilon_0}, & L < 2,\\ a_2\varepsilon^{-\gamma}, & L > 2\end{cases} \tag{7}$$

with $a_1 = 9.48\cdot10^{-16}$, $a_2 = 7.55\cdot10^{-23}$, $\varepsilon_0 = 0.0275$ MeV, $\gamma = 5.64$ [11], and neutrals assumed to be distributed as follows

$$n_{\mathrm{H}_2} = n_0\cdot\mathrm{H}^{\alpha}, \qquad n_0 = 62544.2, \qquad \alpha = -3.7. \tag{8}$$

Expression (7) fits the experimental data presented in [5].

In our simulation the radial diffusion coefficient is taken in the form [2]

$$D^{22} = D_0 L^{10},\ D_0 = 3 \cdot 10^{-14} \tag{9}$$

that corresponds only to the magnetic field stochastic distortion (it is suitable for the qualitative description presented here). Pitch-angle diffusion coefficient will be taken in the model form [3]

$$D^{33} = \sigma \left(\frac{c_3}{c_{\mathrm{cone}}} \right)^{\delta}. \tag{10}$$

This coefficient has two parameters for our investigation: (a) the amplitude value of the pitch-angle diffusion coefficient chosen as $\sigma = 10^{-6}$ and (b) the sharpness of the coefficient, that describes the affect of the cone on proton distribution chosen as $\delta = 1.5$ and pitch-angle cosine on the atmospheric loss cone

$$c_{\mathrm{cone}} = \sqrt{1 - \frac{1}{L^3 \sqrt{4 - 3/L}}}\ . \tag{11}$$

SIMULATION RESULTS

The effective time of all processes that is considered in present paper it is shown in Figures 1a, 1b. From these Figures one can see that for definite values of pitch-angle scattering this process may dominate in some region of phase space even for the equatorial protons (Figure 1a) and always should be taken into account for protons with $c_3 > 0$.

From this figures one may see that charge-exchange process always play the important role and should be taken into account. This term is also very sensitive to the position of the proton trajectory mirror points and so will differ significantly for quite time and for storm time of Earth magnetosphere.

The numerical solution of Equation (1) was done by use of the alternative direction implicit method for two cases. The first one is model case with the proton flux equal to zero at the loss cone. It is a model for comparison with previous two-dimensional calculations carried out in [6] where pitch-angle scattering was omitted. The results of our calculations presented in Figure 2a at least qualitatively reproduced the results of [6]. The second one is a case with proton distribution function equal to zero at the loss cone. Calculated omnidirectional proton flux of energy for different values of L is presented in Figure 2b. Comparing results of Figures 1a and 1b one may see that for $L > 4$ pitch-angle diffusion does not play an important role for protons distribution. On the other hand, for low values of L parameter pitch-angle diffusion is significant and decries the omnidirectional proton flux more than to one-tenth of its former value.

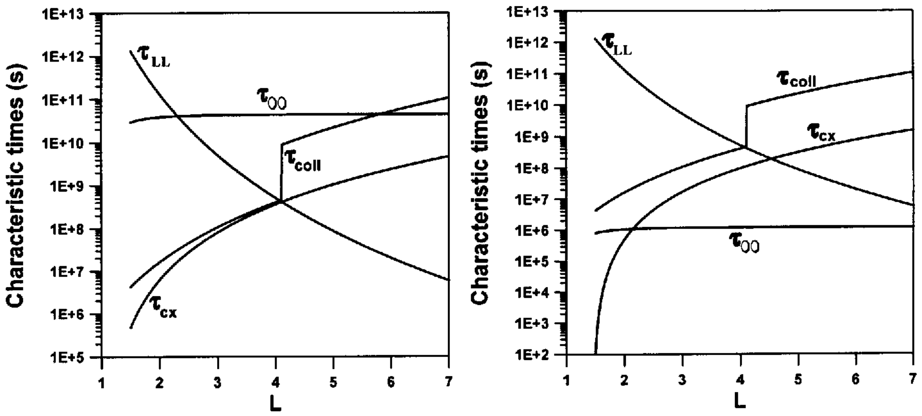

Fig. 1. Effective process times vs. L for protons with E = 1 MeV and c_3 = 0 (*a*); c_3 = 0.9 (*b*)

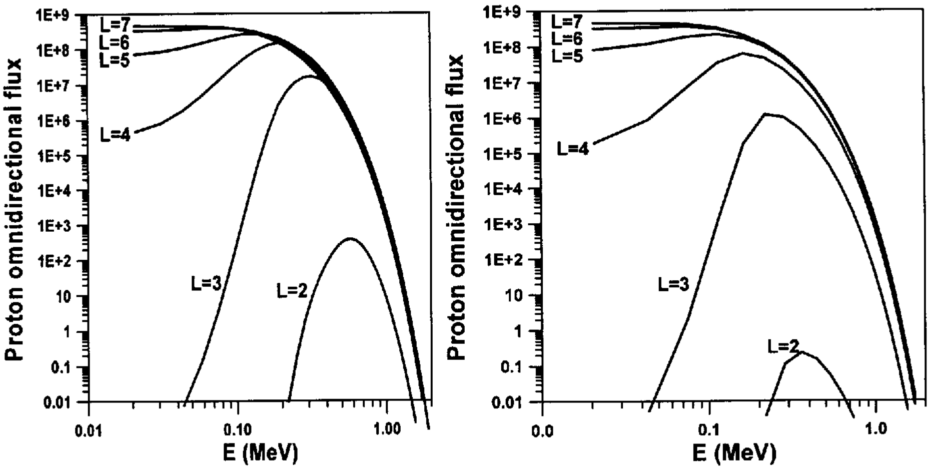

Fig. 2. Proton flux versus energy for the model: *a* — when atmospheric cone loss set to be absent, and *b* — when atmospheric cone loss is taken into account

Present calculations demonstrates that pitch-angle scattering plays the dominant role for proton flux distribution at low values of Mc'Ilvain parameter and should be taken into account in the theoretical investigations.

CONCLUSIONS AND DISCUSSIONS

The model and numerical calculations presented in the paper clarify the role of the pitch-angle scattering for the proton distribution in the Earth plasmasphere. They demonstrates that even a small value of 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.

At the same time approach proposed was based on the assumption that proton distribution function is steady-state. In Figures 1a, 1b one may see that the time required for distribution function to come 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 also the time variation of the proton source and Earth magnetic field geometry.

REFERENCES

1. Albert J. M. // J. Geophys. Res.—1999.—**104**, N A2.—P. 2429.
2. Jordanova V. K., Kistler L. M., Kozyra J. U., et al. // J. Geophys. Res.—1996.—**101**, N A1.—P. 111.
3. Cheng C. Z., Johnson J. R. // J. Geophys. Res.—1999.—**104**, N A1.—P. 413.
4. Chen L. // J. Geophys. Res.—1999.—**104**, N A2.—P. 2421.
5. Toivanen P. K., Pulkkinen T. I., Friedel R. H. W., et al. // J. Geophys. Res.—1999.—**104**, N A5.—P. 10205.
6. Davidson G., Walt M. // J. Geophys. Res.—1977.—**82**.—P. 48.
7. Cornwall J. M. // J. Geophys. Res.—1972.—**77**.—P. 1756.
8. Beutier T., Boscher D. // J. Geophys. Res.—1995.—**100**, N A8.—P. 14853.
9. Speldvik W. // J. Geophys. Res.—1977.—**82**.—P. 2801.
10. Chen M. W., Lyons L. R. // J. Geophys. Res.—1994.—**99**, N A4.—P. 5745.
11. Bashkirov V. F., Panasyuk M. I., Teltsov M. V. // Space Res.—1998.—**36**, N 4.—P. 369.
12. Vette J. I. The NASA/National Space Science Data Center Trapped Radiation Environment Model Program (1964-1991) // NSSDC/WDC-A-R &S 91-29, 1991.