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LOSS EFFECTS FOR ENERGETIC PROTONS ASSOCIATED WITH A MAGNETIC STORM IN THE INNER MAGNETOSPHERE

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Abstract: Development of the ring current is one of major phenomena during a magnetic storm in the Earth's magnetosphere. Ring current protons collide with other particles (*e.g.*, geocoronal hydrogen and plasmaspheric electrons) and lose their energies within a few days. The primary loss processes for ring current protons are considered as; (i) charge exchange with the geocoronal neutral hydrogen, and (ii) Coulomb collision with the plasmaspheric thermal electrons. In order to estimate the loss rate caused by both loss processes numerically, it is essential to trace each particle along their trajectories because the drift paths basically depend on energy, pitch angle, initial position of charged particles and the magnetospheric electric and magnetic fields. For this purpose, we have developed a particle simulation code including the charge exchange and the Coulomb collision as the major loss processes with a time-dependent magnetospheric electric field. A new plasmaspheric density model is also developed to evaluate the Coulomb collision between the ring current protons and the plasmaspheric thermal electrons. This model is a two dimensional and time-development on plasmaspheric number density, derived from a continuity equation along a magnetic flux tube connecting with the conjugate ionospheres in both hemispheres. Using this model, we obtained the electron density distribution in the plasmasphere which was fairly consistent with the one obtained by EXOS-B satellite observation.

In this paper, we demonstrate the trajectory of 100 eV (lower energy) and 100 keV (higher energy) protons associated with a magnetic storm. Their energies are lost effectively by Coulomb collisions more than charge exchange loss process, and hence, thermal electron distribution in the inner plasmasphere gives an important effect for lower and/or higher energy protons.

1. Introduction

It has been assumed that energetic ring current protons decay their energy due to the charge exchange with geocoronal hydrogens and the Coulomb collision with thermal electrons in the plasmasphere. These two loss processes have been investigated by many researchers in the past. WENTWORTH *et al.* (1959) calculated

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lifetime for energetic protons due to the Coulomb collision and compared it with the chargeexchange loss by using a simple plasmaspheric model. KISTLER *et al.* (1989) examined the charge exchange loss effect along their drift paths. TAKAHASHI *et al.* (1990) simulated the ring current protons of monoenergy with 90° pitch angle including the loss process due to charge exchange and wave particle interaction, but they assumed that the lifetime for both processes is expressed by a very simple formula independent of particile's energy etc., that is, a function of a radial distance from the earth. Recently, FOK *et al.* (1993) adapted the Coulomb collision loss effect to the KISTLER *et al.* (1989)'s model by using the hydrodynamic theory.

In order to calculate the Coulomb collision lifetime of ring current protons along their drift paths, we considered a spatial plasmaspheric model which depends on magnetospheric activities. The formation of the plasmasphere is strongly controlled by the large-scale magnetospheric electric field which is generally related to the magnetospheric activity. If the magnetospheric activity is increased, the plasmasphere is eroded by the enhanced convection field. On the other hand, if the activity is relatively low, the plasmasphere is filled with the thermal plasma coming from both conjugate ionospheres; this process is called refilling. CHEN and WOLF (1972) first formulated the refilling rate in the plasmasphere by a simple equation. Since then, various models have been proposed to explain this outflow (*e.g.*, single-stream hydrodynamic model (SINGH *et al.*, 1994), two-stream hydrodynamic model (RASMUSSEN and SCHUNK, 1988), semi-kinetic model (WILSON *et al.*, 1992). But these models are rather complicated and are not so practical to calculate the spatial plasma distribution in the whole plasmasphere. RASMUSSEN *et al.* (1993) showed that the simple continuous equation of CHEN and WOLF (1972) is almost consistent with the complicated numerical models. Therefore, we applied the continuous equation in a magnetic flux tube for two-dimensional equatorial plane to calculate equatorial plasmaspheric density which varies with magnetospheric activities.

2. Theory

2.1. Motion of particles

The motion of a non-relativistic charged particle in an electromagnetic field is described by the Lorentz force equation

$$\frac{\mathrm{d}^2\boldsymbol{R}}{\mathrm{d}t^2}=\frac{q}{m}\left(\boldsymbol{E}+\frac{\mathrm{d}\boldsymbol{R}}{\mathrm{d}t}\times\boldsymbol{B}\right), \tag{1}$$

where $\boldsymbol{R}$, $\boldsymbol{E}$, $\boldsymbol{B}$, m and q are; position of a charged particle, electric field, magnetic field, mass and charge of a particle, respectively. We made following assumptions; (i) the Earth's magnetic field is a dipole, (ii) temporal variation of electromagnetic fields are so slow that the particle motion is well approximated by its guiding center motion, (iii) the first and second adiabatic invariants (μ and J) are conserved, and (iv) the particle motion generates no additional electromagnetic fields. With these assumptions, the bounce-average drift velocity in the geomagnetic equatorial plane is written as

$$\boldsymbol{u}_{\mathrm{D}}=\boldsymbol{F}_{\perp}\times\frac{\boldsymbol{B}}{qB^2}, \tag{2}$$

and

$$\boldsymbol{F}_{\perp}=q\boldsymbol{E}-q(\boldsymbol{\omega}\times\boldsymbol{R})\times\boldsymbol{B}-WG(\alpha_0)\frac{\nabla_{\perp}B}{B}, \tag{3}$$

where α_0 is the equatorial pitch angle, $\boldsymbol{\omega}$ the angular velocity of the Earth's rotation, W the kinetic energy, and $G(\alpha)$ is defined as

$$G(\alpha_0)=\int_0^{\lambda_m}\frac{(2-\sin^2\alpha_0\cdot\sec^6\lambda\sqrt{1+3\sin^2\lambda})(1+\sin^2\lambda)\cos^2\lambda}{(1+3\sin^2\lambda)^2}\mathrm{d}\lambda, \tag{4}$$

where λ and λ_m are latitude and mirror latitude, respectively. Since this integrand has a singular point, it takes a lot of time to calculate the integration. We used the approximate equation for $G(\alpha_0)$ given by EJIRI (1978).

The magnetospheric large-scale electric field is assumed as the Volland-Stern type potential model (VOLLAND, 1973; STERN, 1975). The large-scale electric field potential Φ_E is expressed as,

$$\Phi_E=AR^{\gamma}\sin\phi, \tag{5}$$

and the corotation electric field ($\boldsymbol{E}_{\mathrm{co}}$) is given by

$$\boldsymbol{E}_{\mathrm{co}}=-(\boldsymbol{\omega}\times\boldsymbol{R})\times\boldsymbol{B}, \tag{6}$$

where A is a coefficient of intensity, γ a shape factor, R a distance from center of the earth and ϕ a magnetic local time, respectively. We have used $\gamma=7.3/Kp$ (EJIRI, 1980), and A is a function of Kp given by MAYNARD and CHEN (1975) for $\gamma=2$.

$$A=\frac{0.045}{(1-0.159\,Kp+0.0093\,Kp^2)^3}\ (\mathrm{kV/Re^2}). \tag{7}$$

The radial and longitudinal components of the drift velocity are expressed as

$$u_R=-\frac{\omega}{\gamma}\left(\frac{R}{R_0}\right)^{\gamma+2}R_0\cos\phi, \tag{8}$$

$$u_{\phi}=-\frac{3W_{\parallel}}{k_0a^3}\cdot R\cdot G(\alpha_0)+\omega\left(\frac{R}{R_0}\right)^{\gamma+2}R_0\sin\phi+\omega R, \tag{9}$$

where k_0, a and R_0 are the magnetic intensity at $L=1$, the earth's radius and the stagnation distance at dusk sector for the zero-energy particle. The distance R_0 is defined as

$$R_0=\left(\frac{a^3k_0\omega}{\gamma A}\right)^{\frac{1}{\gamma+1}}. \tag{10}$$

2.2. *The plasmaspheric model*

In order to produce the practical plasmaspheric model in this study, we made the following assumptions; (i) the number of electrons and protons are equal ($n_e = n_i$) in the plasmasphere, (ii) the electron and ion distributions are both isotropic with the same temperatures, $T_e = T_i = 1$ eV, (iii) a continuity equation is conserved in a magnetic flux tube, (iv) the plasmaspheric protons are supplied from a pair of conjugate ionospheres, and (v) protons in a magnetic flux tube are subjected to $\boldsymbol{E} \times \boldsymbol{B}$ drift. BATES and PATTERSON (1961) show that the main process of supplying protons in the plasmasphere is the invertible charge exchange

$$O^+ + H \rightleftharpoons O + H^+ , \tag{11}$$

at the F region of the conjugate ionosphere. Since H^+ and O^+ have the different height profiles, there are differences in altitude where the diffusion becomes a dominant process for each ion. If the plasmasphere is depleted (*e.g.* after a magnetic storm), the reaction of eq. (11) proceeds in the forward direction. The altitude distribution of O^+ ions has a sharp peak at F region in the ionosphere. In this situation, the approximate analytical formula derived by RICHARDS and TORR (1985) is applicable to evaluate the upward flux F at the altitude z_0 which is the lower boundary value of the production region;

$$F = 2.5 \times 10^{-11} T_n^{1/2} n_0(H) n_0(O^+) H(O^+) \quad (\mathrm{cm^{-2}s^{-1}}) , \tag{12}$$

where T_n, $n_0(H)$, $n_0(O^+)$ and $H(O^+)$ are the hydrogen and oxygen ion densities, and oxygen ion scale height, respectively. The subscript 0 refers to the lower boundary height of the production region. The IRI-90 (BILITZA, 1986) and the MSIS-86 (HEDIN, 1987) models are used to obtain the ionospheric quantities.

The conservation equation of total number ions in a flux tube is derived by integrating the continuity equation along a magnetic field line. CHEN and WOLF (1972) proposed the following conservation equation,

$$\frac{D_\perp N}{Dt} \equiv \left(\frac{\partial}{\partial t} + \boldsymbol{u}_\perp \cdot \nabla \right) N \tag{13}$$

$$= \frac{F_N + F_S}{B_i} \tag{14}$$

$$= \frac{F}{B_i} , \tag{15}$$

and

$$N = \int \frac{n}{B} h_s \mathrm{d}s \quad (\mathrm{Wb^{-1}}) , \tag{16}$$

where N is total ion content per unit magnetic flux, n the density of H^+, B_i the magnetic intensity at the conjugate ionospheres, and F_N and F_S the limiting fluxes at the northern and sourthern ionospheres, respectively.

The average density of a magnetic flux tube, $\bar{n}$, is introduced as

$$\bar{n} = \frac{N}{V} , \tag{17}$$

where

$$V = \int \frac{h_s}{B} \, ds \,, \tag{18}$$

is a volume of a flux tube and h_s is coordinate scale factor aligned with the magnetic field line. The conservation eq. (15) is rewritten by using the average density $\bar{n}$,

$$\frac{\partial \bar{n}}{\partial t} = \frac{F}{B_i V} \,, \tag{19}$$

where MURPHY (1980) approximated the volume as

$$V = \frac{32 a L^4}{35 k_0} \sqrt{1 - L^{-1}} \left(1 + \frac{1}{2} L^{-2} + \frac{5}{16} L^{-3}\right) \quad (\mathrm{m^3 Wb^{-1}}) \,, \tag{20}$$

where L is McIlwain's parameter.

The plasmaspheric refilling mechanism has been examined so far, it is still a difficult problem to estimate the loss effects correctly. Hence, there is yet no proper model to describe the time-dependent equatorial density including both the production and loss processes. RASMUSSEN *et al.* (1993) applied an assumption to the refilling process in the plasmasphere by using *"refilling time constant"* concept. With the refilling time constant τ, eq. (19) is rewritten

$$\frac{\partial \bar{n}}{\partial t} = \frac{n_{\mathrm{sat}} - \bar{n}}{\tau} \,, \tag{21}$$

and

$$\tau = \frac{n_{\mathrm{sat}} B_i V}{F} \quad (\mathrm{s}) \,, \tag{22}$$

where n_{sat} is the saturation density in a flux tube.

RASMUSSEN *et al.* (1993) concluded that the average density $\bar{n}$ is nearly equal to the equatorial density n_{eq} with a maximum error less than 10%

$$\frac{\partial n_{\mathrm{eq}}}{\partial t} \simeq \frac{\partial \bar{n}}{\partial t} \,. \tag{23}$$

Then, the equatorial density varies with time

$$n_{\mathrm{eq}} = n_{\mathrm{sat}} (1 - e^{-t/\tau}) \quad (\mathrm{m^{-3}}) \,. \tag{24}$$

The saturation density n_{sat} was obtained from the empirical model, derived from the ISEE satellite and the whistler data set by CARPENTER and ANDERSON (1992). Examples of the calculated equatorial proton density are shown in Fig. 1.

The electron density data measured by the impedance probe (IPS) aboard EXOS-B satellite are compared with this model in order to examine the validity of calculation. The EXOS-B, having the low-inclination elliptical orbit (inclination; 31°, perigee; 225 km, apogee; 25800 km), carried out *in-situ* measurements of electron density in the inner magnetosphere.

In Fig. 2, an example of the EXOS-B observation is shown with the numerical

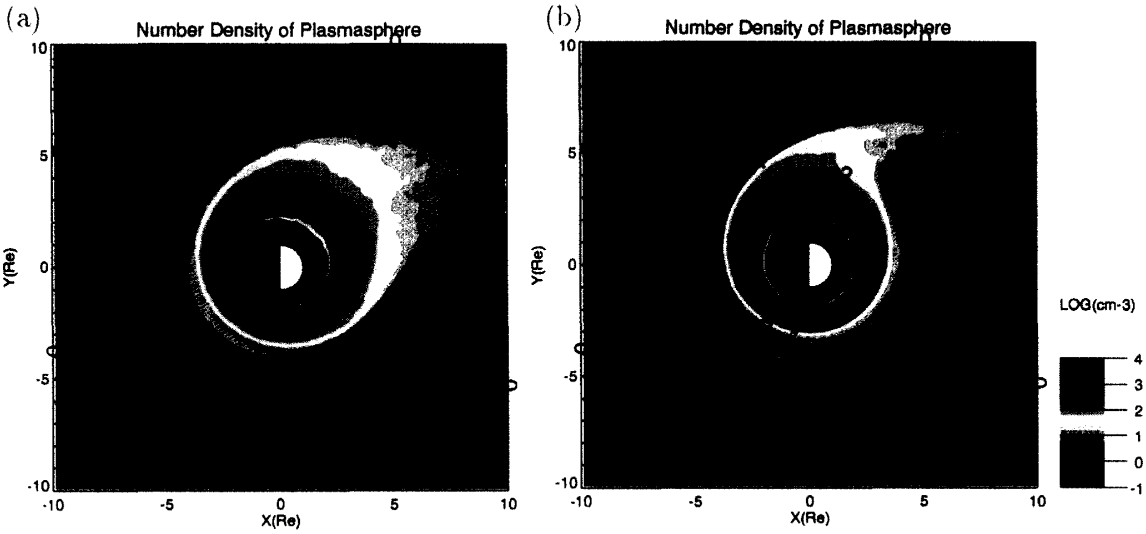

Fig. 1. Examples of the calculated equatorial densities of plasmasphric proton in (cm^{-3}). The calculations are valid for $L \geq 2.25$ in these figures. (a) August 11, 1981 18 UT. (b) August 12, 1981 00 UT.

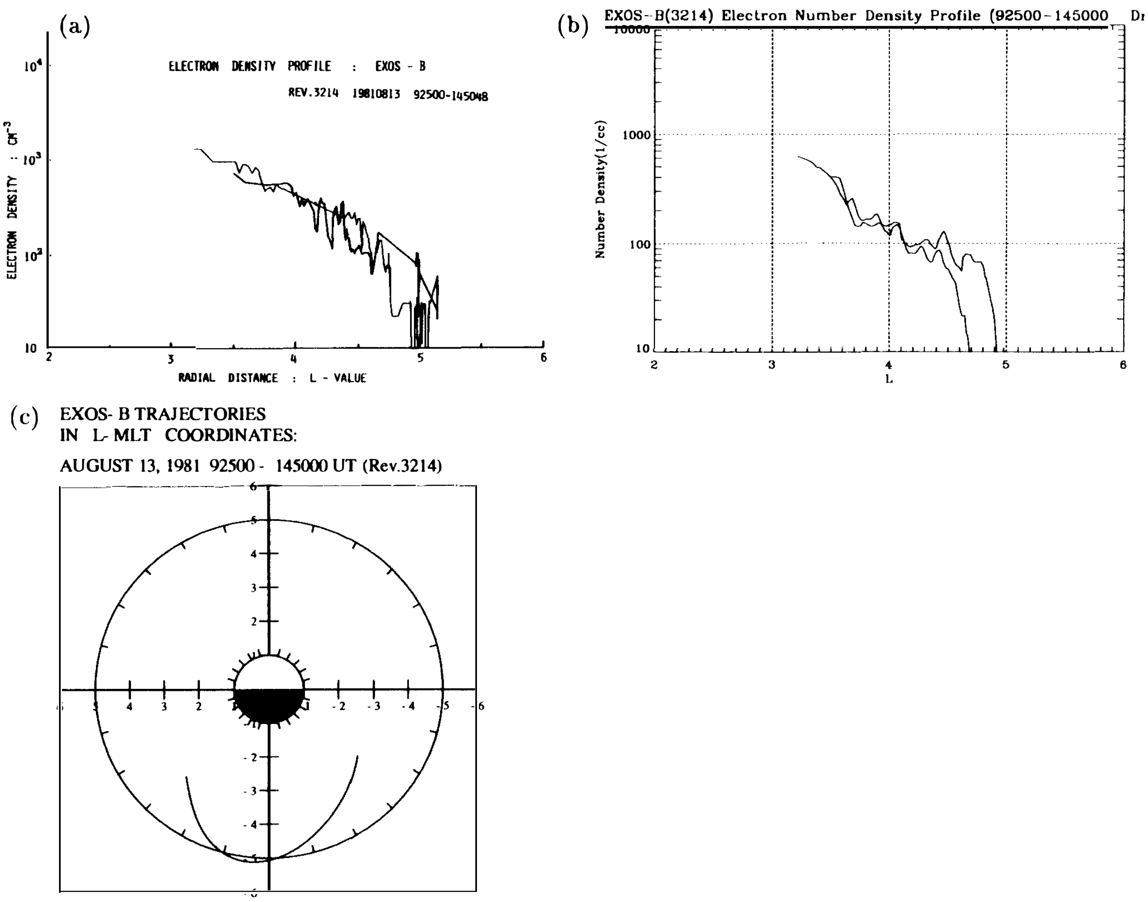

Fig. 2. Comparison of the plasmaspheric electron density between (a) EXOS-B satellite observation and (b) model calculation, and (c) the satellite trajectory projected into MLT-L coordinates.

simulated profile of electron density, *i.e.*, the variation in space and time along its trajectory. In this example, we obtained fairly good agreement between the result by the numerical model and the observation with respect to absolute density and its time-variation, and location of plasmapause.

As for the absolute values in electron density in the plasmasphere, the model simulation gives the values of approximately 100 cm^{-3} at $L=4.5$ and 400 cm^{-3} at $L=3.5$, whereas the observational values are 100 cm^{-3} and 700 cm^{-3}, respectively. The plasmapause crossing by the satellite are $L=5.07$ and $L=4.75$ along the outbound and inbound, respectively. The difference between them is $\Delta L=0.32$ whereas the calculation gives $\Delta L=0.29$. Though the absolute location of the plasmapause is different as is evident in Fig. 2, the change in space and time coincides with the accuracy of about 10%. One of the reasons for the discrepancy between the observational values and those by the model simulation may be due to the accuracy of the convection electric field model which we are assumed to depend on Kp index.

3. Lifetimes for Ring Current Protons

In order to evaluate the collisional loss for the ring current protons quantitatively, 'lifetime' for the ring current protons is defined as *"characteristic time of energetic particles' loss due to collisions with other particles"*. In numerical expression for the lifetime τ is

$$N=N_0(1-e^{-t/\tau}), \tag{25}$$

and

$$\frac{1}{\tau}=\frac{1}{\tau_{ce}}+\frac{1}{\tau_{cc}}, \tag{26}$$

where N_0 is initial density, τ_{ce} and τ_{cc} are lifetimes caused by the charge exchange and the Coulomb collision, respectively.

3.1. *Lifetime of charge exchange loss*

The bounce-average lifetime of charge exchange loss with arbitrary pitch angle is given by

$$\tau_{ce}=\frac{1}{n_H(R)v\sigma(v)}\cos^j\lambda_m, \tag{27}$$

where $n_H(R)$, v and $\sigma(R)$ are the neutral hydrogen density, the velocity of energetic protons, and the charge exchange cross section (JANEV and SMITH, 1993), and $j=3.5$ (SMITH and BEWTRA, 1976).

A Chamberlain model (CHAMBERLAIN, 1963) fitting to the UV imaging photometer data by the DE1 satellite (RAIRDEN *et al.*, 1986) is used for the hydrogen density (n_H) profile. The charge exchange cross section σ is referred to from JANEV and SMITH (1993) which depends only on energy of the proton. In Fig.

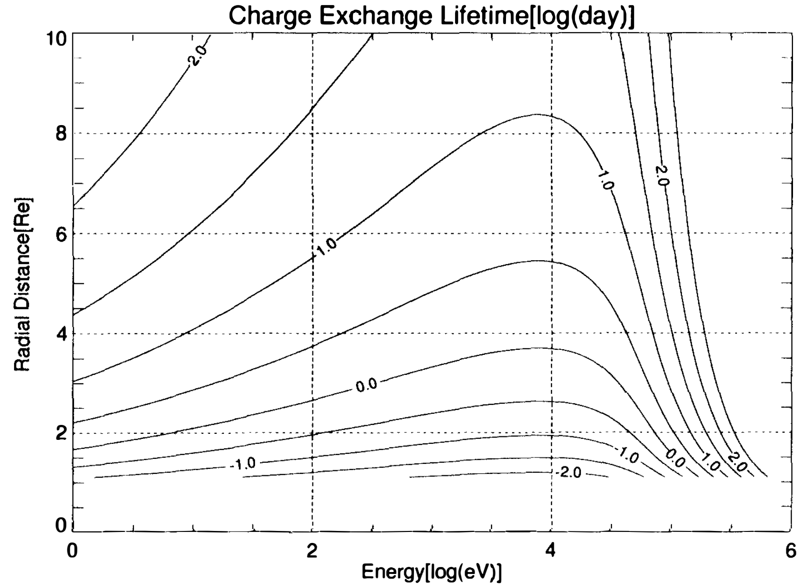

Fig. 3. Equilifetime lines for the ring current protons in logarithmic scale as a function of energy and radial distance from the center of the earth.

3, it is shown the relationship between energy of the protons (the abscissa) and radial distance (the ordinate) in equilifetime lines, *i.e.*, in the figure the logarithmic value of constant lifetime in day is indicated on the curve as a parameter. It is noted that the lifetimes have a peak at about 10 keV; in other words, the ring current protons of about 10 keV will be effectively lost by the charge exchange process.

3.2. *Lifetime of Coulomb collision loss*

Ring current protons lose their energies by the interaction of plasmaspheric

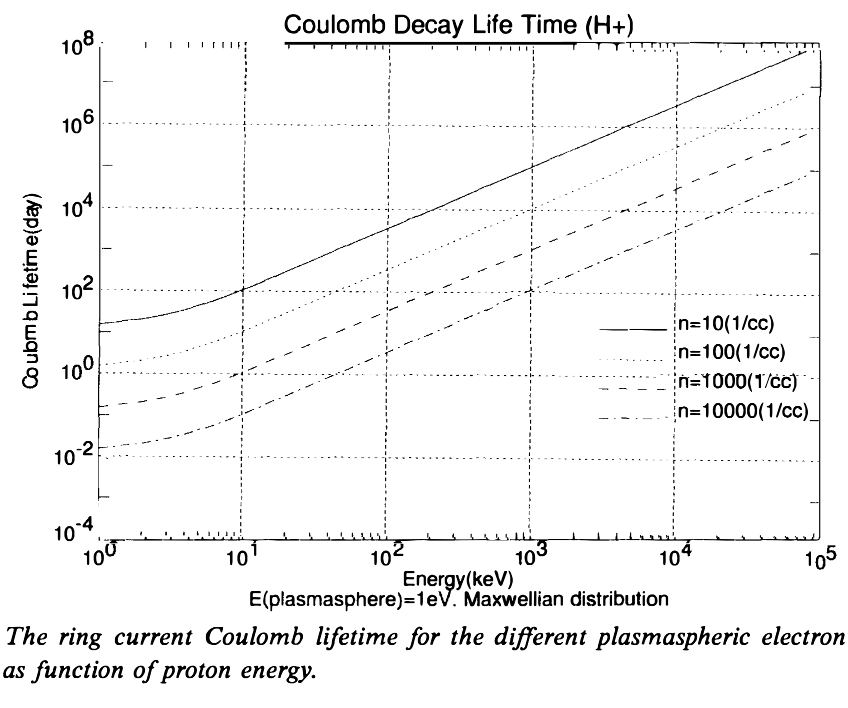

Fig. 4. The ring current Coulomb lifetime for the different plasmaspheric electron densities as function of proton energy.

electrons and ions. These interactions are well approximated to binary collisions and long-range (much greater than the Debye length) Coulomb forces. FOK *et al.* (1991) formulated the Coulomb decay lifetime in this situation based on the Fokker-Planck equation, plasmaspheric electrons and ions being assumed to have Maxwellian distributions. Figure 4 shows the calculated results of the lifetime of the equatorial mirroring protons (the ordinate) due to Coulomb collision loss as a function of energy (the abscissa) for various values in plasmaspheric density.

3.3. Comparison of both lifetimes

The lifetimes of ring current protons mainly depend on the density of scattering particles (*e.g.*, hydrogen of geocorona, electron of plasmasphere) and their energies. In Fig. 5, the contour map of the calculated lifetime of ring current protons is

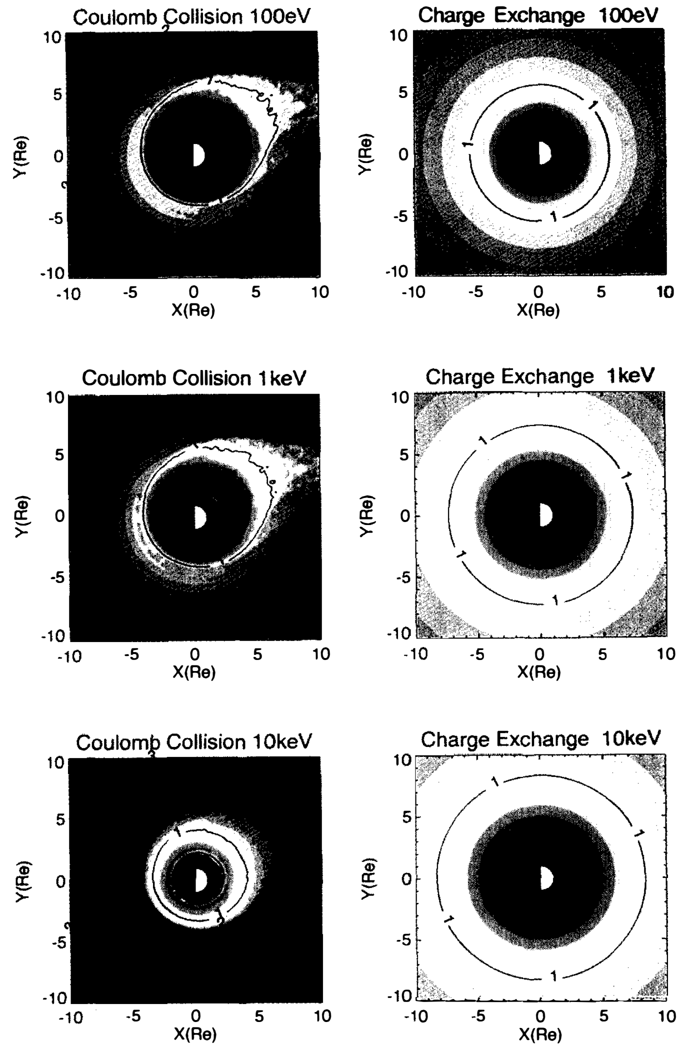

Fig. 5. Comparison of lifetimes due to the charge exchange (left) and the Coulomb collision (right) losses for different proton energies (100 eV, 1 keV and 10 keV). A parameter indicated in the figure is a logarithmic value of the lifetime in day. The calculations are valid for $L \geq 2.25$ in these figures. The Coulomb collision lifetimes are calculated with the time-dependent plasmaspheric model at 16 UT of August 9, 1981.

shown. In general, the charge exchange is the dominant loss mechanism in the inner magnetosphere. However, the Coulomb collision is more effective for the limited energy range from 100 eV to 1 keV protons in the inner plasmasphere.

4. Decay of Ring Current Protons during a Storm

The ring current associated with a magnetic storm is mainly composed of protons with various energies. In order to simulate the decay of the ring current during a storm, we traced trajectories of protons with various energies. The initial and boundary conditions of the simulation are (i) energetic protons with energy 0.01–10 keV are injected from 10 Re nightside of 21 h–3 h MLT at every 0.1 hours into the magnetosphere, (ii) the pitch angle is fixed at $\alpha_0 = 90^\circ$, and (iii) the magnetic and electric fields are the same as the plasmaspheric model; the dipole magnetic field and the Volland-Stern time-dependent electric field.

Kp and *Dst* indices are plotted in Fig. 6 from August 8 to 14, 1981. The energetic protons are injected into the magnetosphere during the period from August 11, 1600 UT to August 12, 1600 UT. Figure 6 seems to indicate that the injection has been finished until 21 UT of August 11. The results of energy density profiles at the 12 MLT meridian obtained from the simulation are presented in Fig. 7. Some injected charged particles would escape toward dayside (out-flow), and this out-flow makes a difference between Fig. 7a and 7b in energy density with no loss (solid line). During the period from 24 to 48 hours after the injection, the charge exchange reduced the energy density of energetic protons from 40% to 78%, while the Coulomb collision reduced only from 10% to 30% at $L = 4$. It is evident that the charge exchange is dominant loss process for the ring current protons in the inner magnetosphere.

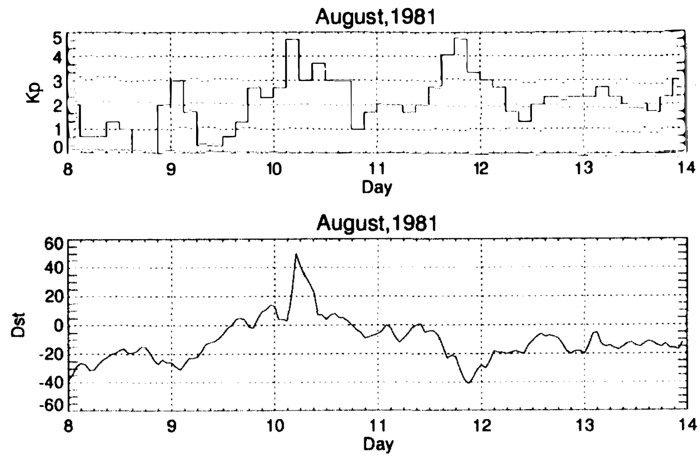

Fig. 6. Kp and Dst indices for the simulation event, August 8–14, 1981.

5. Conclusions

A time-dependent plasmaspheric model has been developed to evaluate the

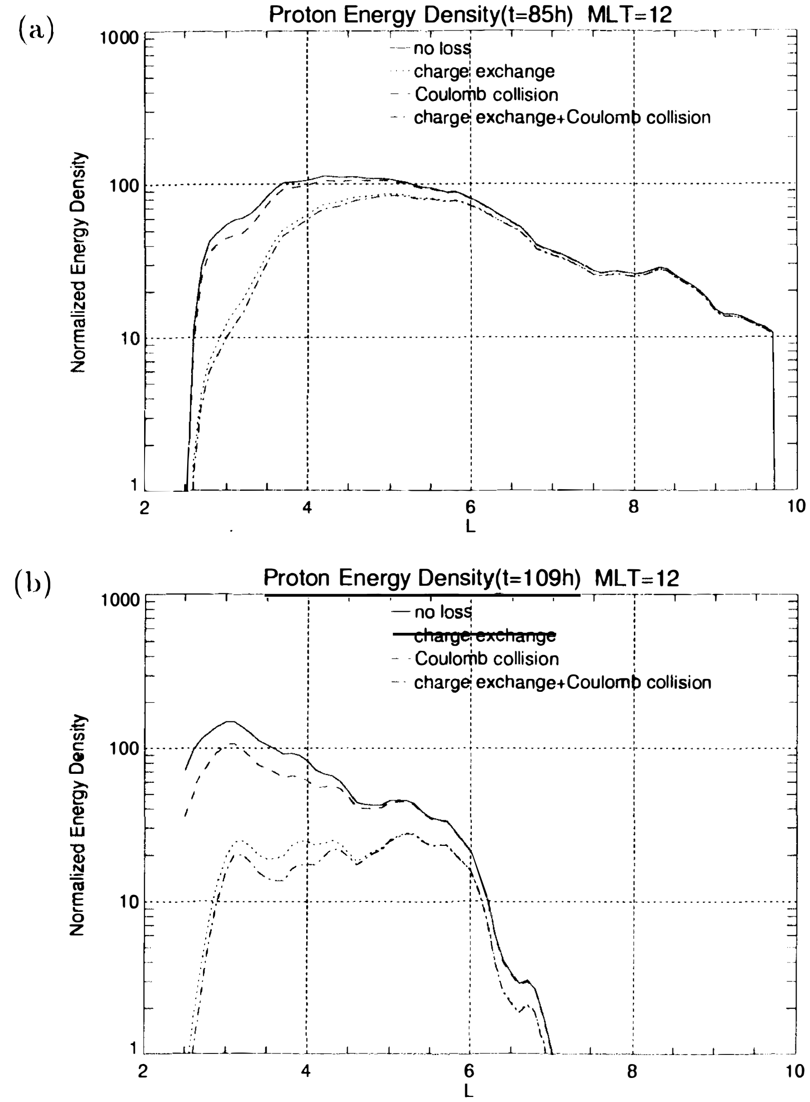

Fig. 7. Energy density profiles at 12 MLT meridian cross section after (a) 24 hours and (b) 48 hours after the injection. Solid line; no loss, dashed line; with Coulomb collision, dotted line; with charge exchange, dashed-dotted line; with Coulomb collision and charge exchange, respectively.

Coulomb collision and the charge exchange lifetimes of the ring current protons quantitatively along the bounce/drift trajectories. Our principal results are as follows: (1) The electron density profiles obtained from this model are fairly consistent with the results of EXOS-B satellite observation. (2) The charge exchange is mainly the dominant loss process in the inner magnetosphere around $L \leq 6$. (3) On the other hand, the lifetime of Coulomb collision for $E < 10$ keV protons is comparable with that of the charge exchange in the plasmasphere. In other words, the plasmasphere is a effective place for sucn protons ($E < 10$ keV) to lose their energy. In order to improve this model more realistically, the following points should be included in the future; (1) multispecies of ions, He^{+}, O^{+} ions, and (2) a realistic magnetospheric convection electric field model which depends on the interplanetary magnetic field (IMF) and solar wind parameters. Also we have a plan to calculate the time constant of recovery phase of a magnetic storm (*e.g.*, *Dst*) and injection process at night side near-tail region during the main phase of a storm.

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