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AN EFFECT OF CHARGE EXCHANGE PROCESSES ON THE PROTON ENHANCEMENT ASSOCIATED WITH A STORM/SUBSTORM IN THE MAGNETOSPHERE

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Abstract: Energetic protons in the radiation belt of the earth's magnetosphere show energy density enhancement associated with geomagnetic storms/substorms, which observation with Explorer 45 evidently revealed as a nose structure in the *E-t* spectrogram inside the plasmasphere.

An attempt has been made to explain this by an injection model in which energetic protons are injected around a nightside geosynchronous orbit with their subsequent inward motions due to a convection electric field possibly driven by the solar wind and a corotation electric field. It is also important to include a loss mechanism in the model inside the plasmasphere since the protons decay due to charge exchange loss processes with geocoronal neutral hydrogen. The loss rate of protons depends on the hydrogen density and charge exchange cross section. In this study, the effect of the charge exchange loss is examined by computer simulation of energetic proton trajectories in the magnetosphere; the hydrogen density being obtained by the Chamberlain model and the charge exchange cross section being adopted from the latest approximate formula. It is concluded that loss processes play an essential role in the energy density distributions of protons in the near earth radiation belts, especially inside L of about 4.

1. Introduction

Storm time ring currents decay by charge exchange loss between protons and geocoronal neutral atomic hydrogen. The rate of decay is a function of the equatorial charge exchange lifetime and the equatorial pitch angle. LIEMOHN (1961) studied the functional dependence of the charge exchange lifetime on the equatorial pitch angle, using the Johnson and Fish model (JOHNSON and FISH, 1960) of neutral atomic hydrogen. SMITH and BEWTRA (1976) proposed an approximate formula for the charge exchange lifetime as a function of the equatorial pitch angle, using Chamberlain model (CHAMBERLAIN, 1963). Independently, COWELY (1976) proposed another approximate formula.

The charge exchange lifetime is determined by the hydrogen density in the exosphere and a charge exchange cross section. JOHNSON and FISH (1960) studied the geocoronal hydrogen density based on observation of nighttime Lyman α radiation, considering the escaping flux, and proposed their model. CHAMBERLAIN

(1963) proposed another model of the geocoronal hydrogen density, adding motion of satellite particles. The cross sections at low energies (0.4–40 keV) were first measured by FITE *et al.* (1960). MCCLURE (1966) measured the cross sections in the energy range of 2–117 keV. JANEV and SMITH (1993) provided an approximate formula in the energy range 0.12 eV–10 MeV.

The induced electric field due to the interplanetary magnetic field of the solar wind exists in the earth's magnetosphere; it is called a convection electric field. Magnetospheric plasmas flow toward the earth from the tail by $E \times B$ drift due to the convection electric field. VOLLAND (1973) proposed a convection electric field model based on the shape of the plasmapause. Similarly, STERN (1975) proposed a model based on the electric field observed at high latitude. GREBOWSKY and CHEN (1975) determined the *Kp* dependence of the convection electric field strength, using midnight plasmapause locations measured by the OGO3 and OGO5 satellites. MAYNARD and CHEN (1975) explained observations of isolated cold plasma regions in the noon-dusk quadrant by the Explorer-45 satellite, using their *Kp* dependence. EJIRI *et al.* (1978) examined *Kp* dependence on the magnetospheric convection electric potential field, EJIRI (1981) also proposed the *Kp* dependence of the convection electric field gradient.

To obtain the equation of motion of a charged particle's guiding center in the equatorial plane, the force acting on the particle needs to be averaged along a bouncing and cyclotron path between mirror points (*e.g.*, ROEDERER, 1970). There have been many approximate formulae for the equation of motion. CHEN (1970) calculated shapes of trajectories of low energy protons with constant uniform convection electric field and showed that the trajectories have quite different particle energies. EJIRI (1978) gave time developments of single particle motion with arbitrary pitch angles by the guiding center approximation using an electric field model not limited to a uniform field. By Explorer-45 satellite, an ion penetration inside the plasmapause was observed as a nose structure in a magnetic storm. EJIRI *et al.* (1980) explained this by a single particle simulation. In this study, we compute the energy flux of the protons and examine the effect of charge exchange loss processes. In a simulation of this study, the strength and the shape of the convection electric field were changed every 3 hours with changing *Kp* value from February 13 to 14, 1972, when a magnetic storm actually occurred. Then we did two simulations with and without the charge exchange loss, and examined how deep protons penetrate inside the plasmapause.

A simulation is carried out under the following basic assumptions.

(1) The geomagnetic field is a dipole with axis perpendicular to the earth's equatorial plane.

(2) The convection electric field is of the Volland-Stern type, and is a function of *Kp* (EJIRI, 1981).

(3) First and second adiabatic invariants are conserved.

2. Magnetic Field and Electric Field Model of Magnetosphere

The dipole type magnetic field in the magnetic equatorial plane is given by the equation

$$B = k_0/r^3, \tag{1}$$

where

$$k_0 = 31100[\gamma R_E^3],$$

r is the radial distance from a center of the earth in the equatorial plane. The convection electric field E is expressed by

$$E = -\nabla \Phi_E. \tag{2}$$

And we use a Volland-Stern type potential field:

$$\Phi_E = AR^\gamma \sin\phi, \tag{3}$$

where

R: distance from the center of the earth (R_E),
ϕ: azimuth (local time from midnight).

In the case of $\gamma=2$, GREBOWSKY and CHEN (1975) determined the coefficient A from the position of the plasmapause observed by the OGO3 and OGO5 satellites:

$$A = \frac{0.045}{(1-0.159Kp+0.0093Kp^2)^3} \quad [\mathrm{kV}/R_E^2]. \tag{4}$$

By the Ejiri model (EJIRI, 1981) γ is also a function of Kp:

$$\gamma = 7.3/Kp. \tag{5}$$

The corotation electric field is induced by the rotation of the earth; its potential is given by:

$$\Phi_c = -k_0\omega/R, \tag{6}$$

where

ω: the angular velocity of the earth (rad/s).

The direction of this electric field is towards the center of the earth. The electric field in the magnetosphere is obtained by adding the above two electric fields.

3. Equation of Motion of Charged Particle with Arbitrary Pitch Angle

EJIRI (1976, 1978) studied the motion of a charged particle which bounces between mirror points in the magnetosphere. The particle drift speed U_D in the magnetic equatorial plane is expressed by the equation

$$\vec{u}_D = \vec{F}_\perp \times \frac{\vec{B}}{qB^2} \tag{7}$$

where

$$\vec{F}_\perp = q\cdot\vec{E} - q(\vec{\omega}\times\vec{R})\times\vec{B} - W\cdot G(\alpha_0)\cdot\nabla_\perp B/B, \tag{8}$$

R: the position vector from the center of the earth,
W: the particle kinetic energy (Joules),
ω: the angular velocity of the earth (rad/s),
α_0: the particle pitch angle in the magnetic equatorial plane.

The first term of eq. (8) is a force due to the convection electric field, the second term is a force due to the rotation of the earth and the third term is a force due to the gradient and curvature of the magnetic field (for the function $G(\alpha_0)$ see EJIRI (1978)).

4. Charge Exchange Theory

4.1. Charge exchange lifetime

SMITH and BEWTRA (1978) studied the decay of ions which form a ring current by charge exchange loss with the atomic hydrogen surrounding the earth. A proton bouncing between mirror points in the magnetosphere collides with neutral atomic hydrogen and causes charge exchange. This is called the charge exchange process and is given by the formula:

$$H^{+(*)} + H = H^{(*)} + H^+, \tag{9}$$

where * denotes an energetic state. Protons are lost by this process and equatorial ring currents decay. The rate of the decay is determined by the charge exchange lifetime.

In the case of pitch angle 90 degrees, a proton stays on the equatorial plane and the charge exchange lifetime becomes:

$$\tau_e = 1/(n(r_0)\sigma v), \tag{10}$$

where

$n(r_0)$: neutral atomic hydrogen density on the equatorial plane, r_0 being radial distance from the center of the earth,
v: velocity of the proton,
σ: charge exchange cross section between the proton and atomic hydrogen.

τ_e is the mean lifetime of charge exchange loss for a proton confined to the equatorial plane. In the case of an arbitrary pitch angle, the proton bounces between mirror points on the earth's magnetic field. For the proton mirroring at latitude λ_m, the effective charge exchange lifetime for the mirroring proton τ_m is given by:

$$\tau_m = \tau_e \cos^j \lambda_m , \tag{11}$$

where

λ_m: a mirror latitude of the proton.

The approximate value of j for the Johnson and Fish model is 6 (LIEMOHN, 1961); for the Chamberlain model it is 3.5 (SMITH and BEWTRA, 1976).

If the number of the protons is N_{t0} at time $t0$, $N_{t0+\Delta t}$ at $t0+\Delta t$ is evaluated from the equation:

$$N_{t0+\Delta t} = N_{t0} \exp(-\Delta t/\tau_m) . \tag{12}$$

4.2. Geocoronal hydrogen density

The neutral atomic hydrogen density surrounding the earth is given by the Chamberlain model (CHAMBERLAIN, 1963). The hydrogen density is a function of the hydrogen temperature T_c at the exobase, the exobase altitude R_c (called the critical level), and the hydrogen density N_c. In the exosphere above the exobase, it is possible to ignore the particle collisions that occur in unit time. The thermal energy from below the exobase and the gravity control the density. Below the exobase, it is not possible to ignore particle collisions. In the exosphere, the atomic hydrogen has a hyperbolic orbit or an elliptic orbit. In the case of a hyperbolic orbit, the atomic hydrogen escapes from the earth. It returns in the case of an elliptic orbit. CHAMBERLAIN (1963) added a satellite particle to this model. The satellite particle is generated by a small numbers of collisions above the critical level R_c. Above the satellite critical altitude R_{sc}, it is possible to ignore the creation of satellite particles by collision. The particles have three kinds of orbits:

Ballistic particle: The perigee of the elliptic orbit is below the critical level.
Satellite particle: The perigee of the elliptic orbit is below the satellite critical altitude and above the critical level.
Escaping particle: The orbit is hyperbolic.

The neutral atomic hydrogen density for the Chamberlain model (CHAMBERLAIN, 1963) is given by the expression

$$n(r) = N_c \exp(-(\lambda_c - \lambda(r))\zeta(\lambda) , \tag{13}$$

where

$$\lambda(r) = G\mu M/(kT_c r) , \tag{14}$$

G: gravity constant 6.672×10^{-11} ($m^3/(kg\cdot s^2)$),
μ: mass of the earth 5.974×10^{24} (kg),
M: mass of atomic hydrogen 1.6726×10^{-27} (kg),
k: Boltzmann constant 1.3806×10^{-23} (J/K),
T_c: temperature of exobase (K),
N_c: atomic hydrogen density at the exobase (cm^{-3}),

r: radial distance from center of the earth (km).

When the altitude of the exobase is 500 km, then $r=6371+500$ km and

$$\lambda_c = 7028/T_c. \quad (15)$$

For every three kinds of particles, partition functions ζ are given by the expressions

$$\zeta_{bal}(\lambda) = \frac{2}{\sqrt{\pi}}\left[\gamma\left(\frac{3}{2}, \lambda\right) - \frac{(\lambda_c^2-\lambda^2)^{1/2}}{\lambda_c} e^{-\Psi_1}\gamma\left(\frac{3}{2}, \lambda-\Psi_1\right)\right] \quad (16a)$$

$$\zeta_{sat}(\lambda) = \frac{2}{\sqrt{\pi}} \frac{(\lambda_c^2-\lambda^2)^{1/2}}{\lambda_c} e^{-\Psi_1}\gamma\left(\frac{3}{2}, \lambda-\Psi_1\right) \quad (16b)$$

$$\zeta_{esc}(\lambda) = \frac{1}{\sqrt{\pi}}\left[\frac{\sqrt{\pi}}{2} - \gamma\left(\frac{3}{2}, \lambda\right) - \frac{(\lambda_c^2-\lambda^2)^{1/2}}{\lambda_c} e^{-\Psi_1}\left(\frac{\sqrt{\pi}}{2} - \gamma\left(\frac{3}{2}, \lambda-\Psi_1\right)\right)\right] \quad (16c)$$

where

$$\Psi_1 = \lambda^2/(\lambda+\lambda_c). \quad (16d)$$

A γ is an incomplete gamma function of the first kind.
Below the satellite critical altitude R_{sc}, the partition function ζ becomes

$$\zeta = \zeta_{bal} + \zeta_{sat} + \zeta_{esc}. \quad (17)$$

When $r > R_{sc}$, a satellite particle which has a perigee between R_c and R_{sc} is a ballistic particle; then ζ becomes:

$$\zeta = \zeta_{esc}(\lambda, \lambda_c) + \zeta_{bal}(\lambda, \lambda_{cs}). \quad (18)$$

where $\Psi_1 = \lambda^2/(\lambda+\lambda_{cs})$. The satellite critical altitude R_{sc} is deduced to be 2.5 R_c from measurement of Lyman-α radiation in the earth's upper atmosphere. A profile of the neutral atomic hydrogen density in the Chamberlain model is shown in Fig. 1.

4.3. *Charge exchange cross section*

When there is one neutral atomic hydrogen per unit volume, in the time that a proton travels a unit distance, the probability of charge exchange by collision is called the charge exchange cross section. Experimental values have been collected by JANEV and SMITH (1993; see Table 1) and can also be expressed by an approximate formula:

$$\sigma = \frac{10^{-16} A_1 \ln(A_2/E + A_6)}{1 + A_3 E + A_4 E^{3.5} + A_5 E^{5.4}} \text{ [cm}^2\text{]}, \quad (19)$$

where

E: proton energy (keV),
$A_1 = 3.2345$,

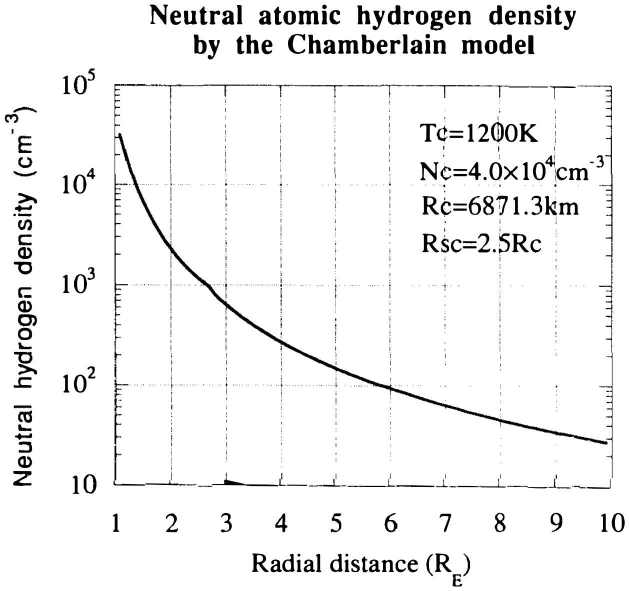

Fig. 1. Profile of the geocoronal neutral atomic hydrogen density from a Chamberlain model.

Table 1. Experimental values of charge exchange cross sections for proton and neutral atomic hydrogen collected by JANEV *and* SMITH *(1993).*

Energy (eV/amu)	Velocity (cm/s)	Cross section (cm^2)
1.20E−01	4.79E+05	4.96E−15
2.00E−01	6.21E+05	4.70E−15
5.00E−01	9.82E+05	4.33E−15
1.00E+00	1.39E+06	4.10E−15
2.00E+00	1.96E+06	3.83E−15
5.00E+00	3.11E+06	3.46E−15
1.00E+01	4.39E+06	3.17E−15
2.00E+01	6.21E+06	2.93E−15
5.00E+01	9.82E+06	2.65E−15
1.00E+02	1.39E+07	2.44E−15
2.00E+02	1.96E+07	2.22E−15
5.00E+02	3.11E+07	1.97E−15
1.00E+03	4.39E+07	1.71E−15
2.00E+03	6.21E+07	1.44E−15
5.00E+03	9.82E+07	1.10E−15
1.00E+04	1.39E+08	7.75E−16
2.00E+04	1.96E+08	4.45E−16
5.00E+04	3.11E+08	9.93E−17
1.00E+05	4.39E+08	1.01E−17
2.00E+05	6.21E+08	6.09E−19
5.00E+05	9.82E+08	6.03E−21
1.00E+06	1.39E+09	1.57E−22
2.00E+06	1.96E+09	3.78E−24
5.00E+06	3.11E+09	2.56E−26
1.00E+07	4.39E+09	5.99E−28

Accurancy: $1\times10^{-4} < E(\mathrm{keV/amu}) \le 1\times10^{-2}$: 10%; $1\times10^{-2} < E(\mathrm{keV/amu}) \le 1$: 10–15%; $1 < E(\mathrm{keV/amu}) \le 1\times10^{2}$: 5–10%; $1\times10^{2} < E(\mathrm{keV/amu}) \le 2\times10^{3}$: 10–20%; $2\times10^{3} < E(\mathrm{keV/amu}) \le 1\times10^{4}$: 20–40%.

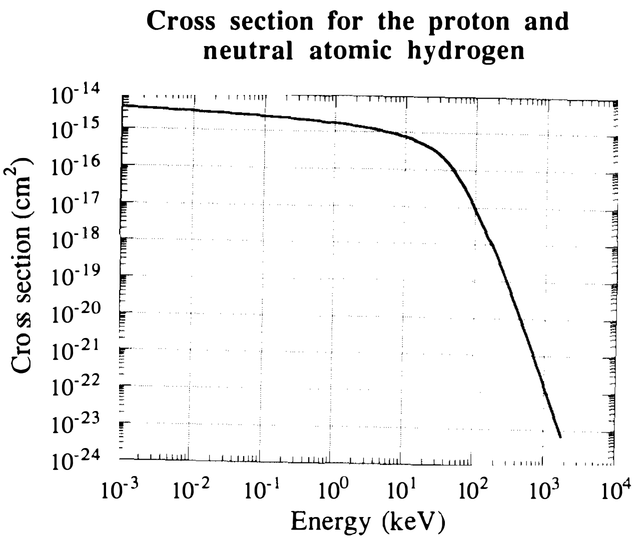

Fig. 2. Energy dependence of charge exchange cross sections by an approximate formula of JANEV *and* SMITH *(1993).*

$$A_2 = 235.88,$$
$$A_3 = 0.038371,$$
$$A_4 = 3.8068\text{E-}06,$$
$$A_5 = 1.1832\text{E-}10,$$
$$A_6 = 2.3713.$$

The mean error of the approximate formula is 2.3%, the maximum error being 5.4% at 1.2 keV. A profile of the charge exchange cross section by this eq. (19) is shown in Fig. 2.

5. Discussion and Conclusions

EJIRI *et al.* (1980) examined the nose structure observed by Explorer-45, and provided boundary shapes of ion penetration by single particle simulation and successfully explained the formation of the nose structures. In this study, the simulation is not a single particle one, but it calculates the energy flux of the protons and includes charge exchange loss of particles.

In this simulation, initial energies of the protons are from 0.03 to 50 keV divided by 30 bins of energy (log-scale). The initial number of protons is the same for all energies. Initial pitch angles are from 0° to 90° in 10° steps. The initial radial position is $10R_E$. Initial azimuthal positions are from 21 MLT to 3 MLT in 0.1 hour steps. The protons are injected in 0.1 hour steps. The simulation period is 48 hours with 0.1 hour steps. The *Kp* values are used at the event of February 13th–14th, 1972. These parameters are summarized in Table 2.

Resultant profiles of the energy density at 0 MLT (midnight) which were computed by the simulation are shown in Figs. 3a, b and c; the energy densities are relative values. They are respectively after an elapsed time of 6, 12 and 48 hours

Table 2. Parameters for the simulation.

Initial energy: 0.03–50 keV (30 bins)
Initial pitch angle: 0–90° (10° step)
Initial position: 10 R_E
21 MLT–3 MLT (0.1 hour step).
The proton was inject with 0.1 hour step.
Simulation time: 48H (0.1 hour step)
Kp values: February 13th–14th, 1972.

Day	UT (hour)	*Kp*		Day	UT (hour)	*Kp*
2/13	0–3	1/3		2/14	0–3	4
	3–6	2+1/3			3–6	3+1/3
	6–9	1+1/3	9:36 SC		6–9	3
	9–12	4+2/3	11:16 onset		9–12	2+1/3
	12–15	4+1/3			12–15	1
	15–18	4+1/3			15–18	2
	18–21	4			18–21	3
	21–24	4			21–24	4

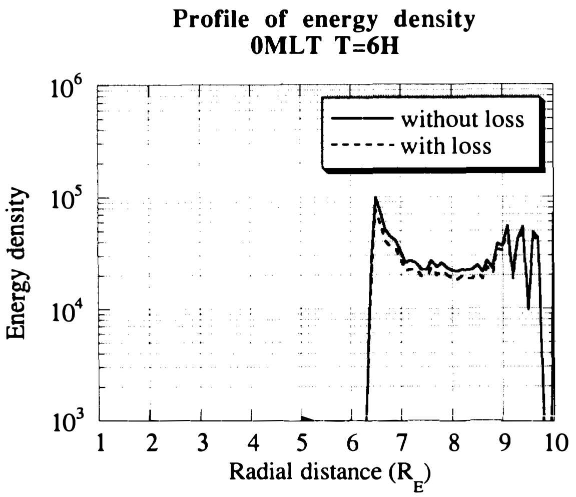

Fig. 3a.

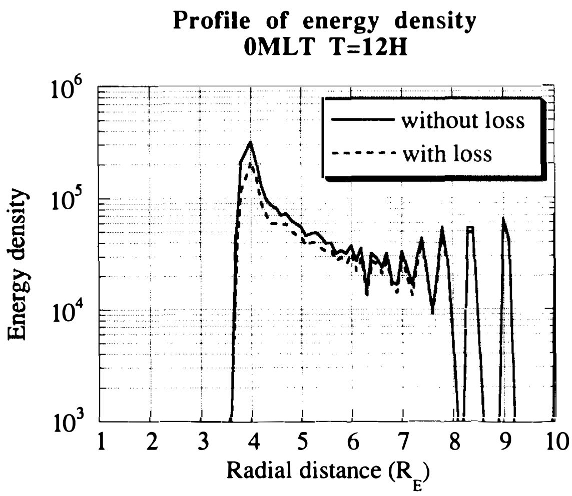

Fig. 3b.

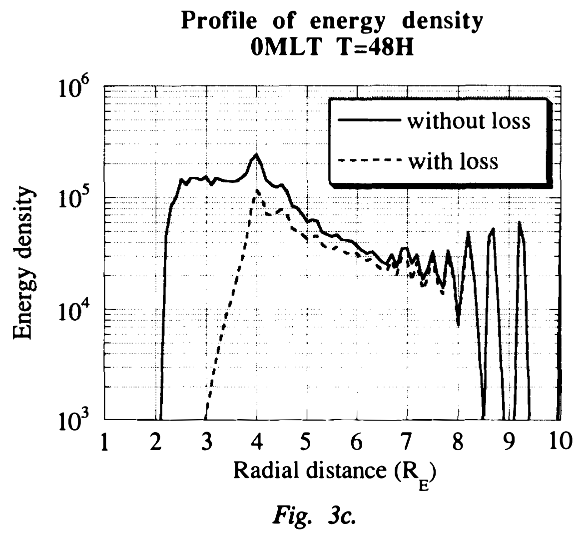

Fig. 3c.

Fig. 3. Profiles of resultant energy density by the simulation. The solid line is the profile without a charge exchange loss; the dotted one is the profile with the loss. The elapsed times are 6, 12 and 48 hours corresponding to Figs. 3a, b and c, respectively. The energy densities are relative values.

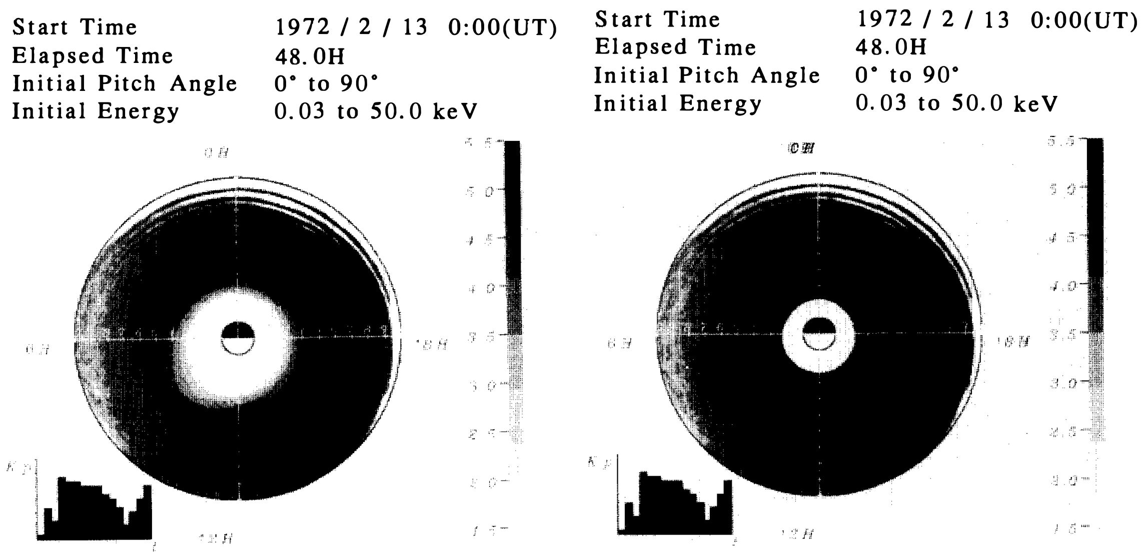

Fig. 4a. *Fig. 4b.*

Fig. 4. The resultant energy density distribution in the equatorial plane for protons. The elapsed time is 48 hours. The cases without and with charge exchange loss correspond to Figs. 4a and b, respectively. The diameter of the circle is 10 R_E. The energy density is shown by a gray scale (log scale of relative value). The Kp history for the event of February 13th–14th, 1972 is illustrated in the lower left.

from the start of injection. Solid lines are the profile without the charge exchange loss, dotted lines are the profile with the loss. There are discontinuities near $10R_E$, because the particle injection interval is 0.1 hours. In Figs. 3a and b, the elapsed time being 6 and 12 hours, the energy density with loss and without loss are not different. In Fig. 3c, in the case with loss, the energy density decreases rapidly at around $4R_E$; in the case without loss it decreases rapidly at around $2R_E$. This result suggests that the charge exchange loss cannot be ignored on the motion of the proton inside $4R_E$. Figures 4a and b are the energy density distribution in the equatorial plane for the protons. The elapsed time is 48 hours. The case without the loss and with the loss correspond to Figs. 4a and b, respectively. The diameter of the circle is $10R_E$. The energy density is shown by a gray scale (log scale). The small graph in the lower left side is *Kp* history in the event of February 13–14, 1972. From the single particle trajectory simulation by EJIRI (1978), protons having initial energies less than 1.6 keV at $10R_E$ penetrate in the region around 3–$4R_E$ by the $E \times B$ drift. In the region of 3–$4R_E$, the protons rotate around the earth by the grad-B drift. The protons decay by charge exchange loss, because the hydrogen density is dense and protons stay in the region of 3–$4R_E$ for many hours. EJIRI *et al.* (1980) showed shapes of the nose structures obtained by single particle simulation, but distances of the inner edges of the nose structures were different from the observed ones. In this simulation with the loss, the distance of the inner edge is similar to the observation result.

The simulation needs to include an electron loss (*e.g.* wave-particle interaction), time variations of the magnetic field, etc. in order to make a self-consistent model. Recently, FOK *et al.* (1991) showed that a decay by Coulomb collisions is comparable to the charge exchange decay when the energy of the protons is less than 7 keV or more than 200 keV. Therefore, Coulomb collisions play an essential role in the ring current decay process and should be introduced in this simulation. But this is beyond the scope of this study.

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