Ring Current Response to Impulsive Southward IMF: A Cause of Second Development of the *Dst* Index

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We simulate particle motions in a realistic magnetospheric model under an impulsive dawn-dusk electric field and show an oscillation of the ring current intensity. This oscillation is caused by the effect of the asymmetric configuration of magnetospheric magnetic field. It is suggested that this effect explains the second development of the *Dst* often observed during recovery of storms after an impulsive southward IMF or in the impulse response function of the *Dst* to the IMF southward component.

1. Introduction

The relationship between the ring current development and the solar wind parameters has been studied for many years (e.g. WILLIAMS, 1983, 1985). BURTON *et al.* (1975) empirically showed the simple relationship between the *Dst* index and the interplanetary electric field $-V \cdot B_z$ and predicted the *Dst* index from solar wind data. IYEMORI *et al.* (1979) and IYEMORI and MAEDA (1980) tried to predict the *Dst* index from solar wind data (IMF B_z) by the method based on Wiener's linear prediction theory and found that the response function of the *Dst* is roughly consistent with what is expected from the result of BURTON *et al.* (1975), but that there exists a second development with a time lag of about five hours after the main development. MCPHERRON *et al.* (1986) obtained a similar result which also showed the second development of the *Dst* index. Figure 1 shows the result of a superposed epoch analysis of storms with an impulsive southward IMF-B_z. We select 6 cases from 1964–1984 which show a strong impulsive southward IMF followed by the prolonged northward IMF and superposed the IMF B_z and the *Dst* index as the zero-crossing of the IMF B_z from southward to northward to coincide. This also shows a second development consistent with the impulse response function. However, the mechanism is not clear yet.

In order to understand the growth and recovery of the ring current, it is essential to estimate the effect of a time varying electric field on particle motions. SMITH *et al.* (1979) simulated particle motions in a time varying electric field and visualized a particle trapped process accompanied with a decrease of the dawn-dusk electric field. Previously, using a monochromatic model (single energy and single pitch angle model) developed by LEE *et al.* (1983), we simulated the ring current of a storm recovery phase with a dipole magnetic field under time varying dawn-dusk electric fields and calculated the *Dst* variation accompanied with a decrease of cross-tail electric field (TAKAHASHI *et al.*,

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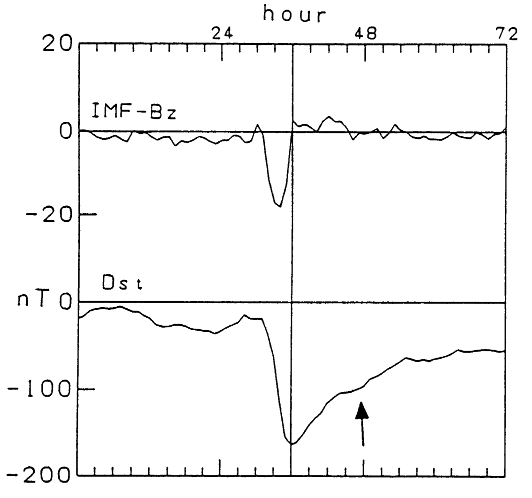

Fig. 1. Upper and lower panels show superposition of the IMF-B_z and the *Dst* index of storms having an impulsive southward turning of the IMF-B_z. The arrow indicates the second development.

1990). On the other hand, ONDOH and AIKYO (1987) and TAKAHASHI and IYEMORI (1989, 1990) have studied the effect of the magnetospheric magnetic field configuration on particle motion using MEAD and FAIRFIELD's (1975) model and found a day-night asymmetry of particle flow pattern. In this paper, we estimate the magnetic field disturbances (*Dst*) caused by particles moving in the model magnetosphere of MEAD and FAIRFIELD (1975) and examine the effect of the realistic magnetospheric structure on the development of the storm-time ring current.

2. Method

In order to calculate the *Dst* response to an impulsive southward IMF, we simulate the motions of particles injected from the magnetotail region into the inner magnetosphere by using MEAD and FAIRFIELD's (1975) model under a time varying electric field. Particle injection is caused by an increase of the cross-tail electric field (LEE *et al.*, 1983). We assume that the electric field is the sum of the corotating electric field and a Volland-Stern type dawn-dusk electric field (VOLLAND, 1973). We calculate the corotating electric field by the finite difference of the electric potential on mesh points, which are obtained by mapping along the magnetic field line from the earth surface to equatorial plane (TAKAHASHI and IYEMORI, 1990). The dawn-dusk electric field is given by

$$E_{dd} = -\operatorname{grad}\Phi, \qquad \Phi = Ar^2\sin\phi, \qquad A = (1/2)\Delta\Phi/y^2, \tag{1}$$

$\Delta\Phi$: cross tail potential difference.

The drift velocity with a 90° pitch angle particle is (e.g. NORTHROP, 1983)

$$\boldsymbol{u}_d = -\boldsymbol{B} \times (e\boldsymbol{E} - \mu\operatorname{grad}B - m(\boldsymbol{u}\operatorname{grad})\boldsymbol{E} \times \boldsymbol{B}/B^2)/(eB^2). \tag{2}$$

We inject 50 simulation particles (pitch angle=90°) from $r=13$ Re, $-60°<\phi<60°$ with a density weight given by

$$N = (n_0 E_{CT}/B) L_z \Delta t (\cos\phi) \Delta\phi, \tag{3}$$

$$n_0 = 0.5\ \mathrm{cm}^{-3}, \quad L_z = 10\ \mathrm{Re},$$

$$E_{CT} = \Delta\Phi/2y\text{: cross tail electric field.}$$

We also include the loss process due to charge exchange and wave particle interaction. We assume the life time as LEE *et al.* (1983)

$$N(t+\Delta t) = N(t)(1 - \Delta t/T(r)), \tag{4}$$

$$T(r) = T_A (r/r_A)^2, \quad r_A = 6\ \mathrm{Re},$$

which are close to the observed value (TINSLEY and AKASOFU, 1982).

We regard the variation of the magnetic field at the center of the earth, ΔB, as the *Dst* index. ΔB is obtained as LUI *et al.* (1987) and WODNICKA (1989).

$$\Delta B = \mu_0/4\pi\mu \int d\phi \int dr/r(dn/dr - n/B(\mathrm{rot}\,B)_\phi). \tag{5}$$

The effect of the impulsive southward IMF is modeled as follows.

00 hr–18 hr: filling the model magnetosphere with particles under the condition of $\Delta\Phi=10$ kV.

18 hr–20 hr: increase of $\Delta\Phi$ from 10 kV to 100 kV.

20 hr–22 hr: decrease of $\Delta\Phi$ from 100 kV to 10 kV.

22 hr–: $\Delta\Phi=10$ kV.

3. Result and Discussion

First we examine a monochromatic ring current in the dipole magnetic field. Figure 2 shows the number of protons which stay in the model magnetosphere and the magnetic field variation at the center of the earth which corresponds to the *Dst* index during our storm model. The injected energies of protons are 2, 3, 5 and 10 keV in Figs. 2(a), 2(b), 2(c) and 2(d), respectively. It should be noted that protons gain energy drifting along the electric field and that the energy reaches several tens to one hundred keV. We determine the position of the dayside magnetopause as that of Mead and Fairfield's model of $Kp=0$. Accompanied with an increase of $\Delta\Phi$, ΔB develops (18 hr–20 hr). From 20 hr to 22 hr, although $\Delta\Phi$ decreases, ΔB increases. This is caused by untrapped protons which have not flowed out yet. After the main development of ΔB, there exists only a gradual recovery by charge exchange loss of trapped particles and the second development does not exist.

Next we estimate the effect of a realistic magnetospheric magnetic field. Figures 3(a), 3(b), 3(c) and 3(d) show the result of 2, 3, 5 and 10 keV protons for Mead and Fairfield's model of $Kp=0$. The parameters are the same as those in the case of the dipole magnetic field. After the main development of ΔB, ΔB recovers more rapidly than in the case of the

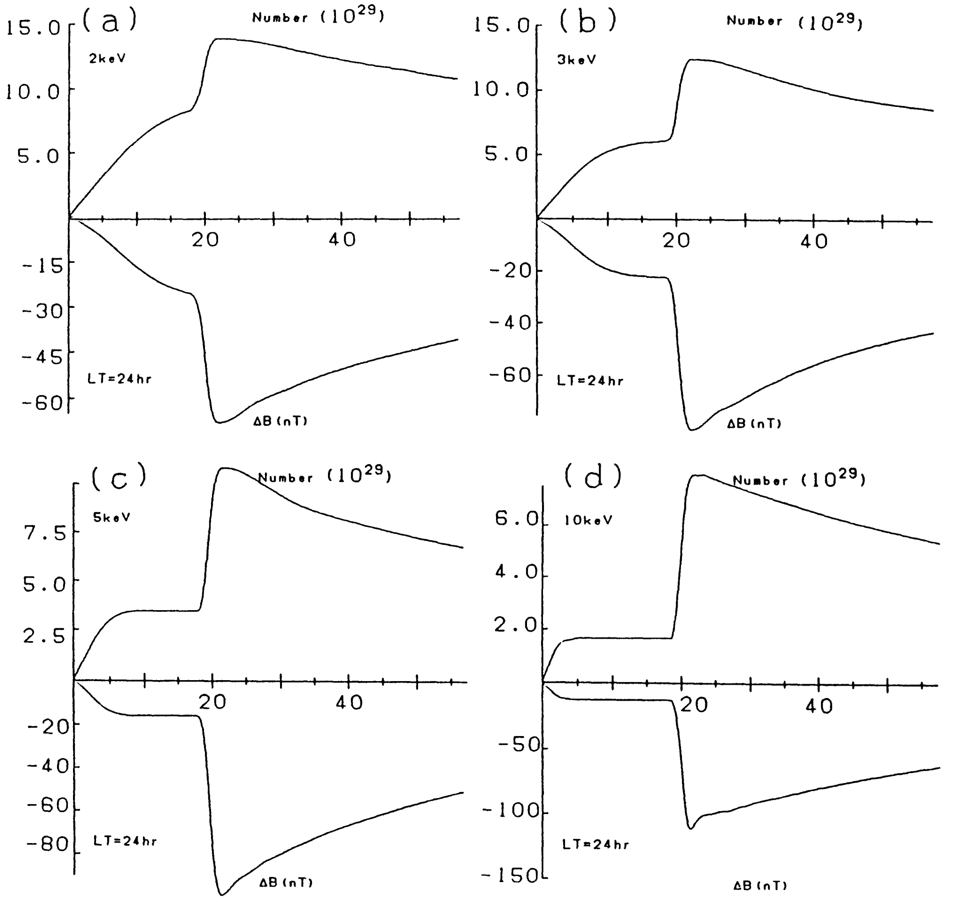

Fig. 2. Lower and upper parts of each figure show time development of the magnetic field at the center of the earth (ΔB) and that of a number of particles (sum of N_i) in the model magnetosphere (dipole magnetic field) for monochromatic ring currents of 2, 3, 5 and 10 keV protons of pitch angle=90° in the model storm I with life time=24 hr.

dipole. This is caused by the asymmetry of the magnetic field. For Mead and Fairfield's model, the gradient and curvature drift speed is faster on the night side than on the dayside. A proton which drifts from midnight can not reach the noon meridian and flows out from duskside magnetopause (TAKAHASHI and IYEMORI, 1989). On the other hand, in the dipole magnetic field, particle trajectories are symmetric with the dawn-dusk meridian.

After the main development, there exists an oscillation in ΔB but not in particle number. This oscillation is also caused by the configuration of the magnetic field. In order to understand this mechanism, we present the time development of particle distribution in the magnetosphere model during an impulsive storm, Fig. 4. Every 4 min, 5 protons whose energy is 5 keV and whose pitch angle is 90° are injected. Particles are trapped after the decrease of $\Delta\Phi$ and drift around the earth. The interval of $\Delta\Phi > 10$ kV (i.e. 4 hours) is too short for the injected particles to fill whole azimuthal angle and the trapped particles form an azimuthal anisotropy in particle distribution. This anisotropic

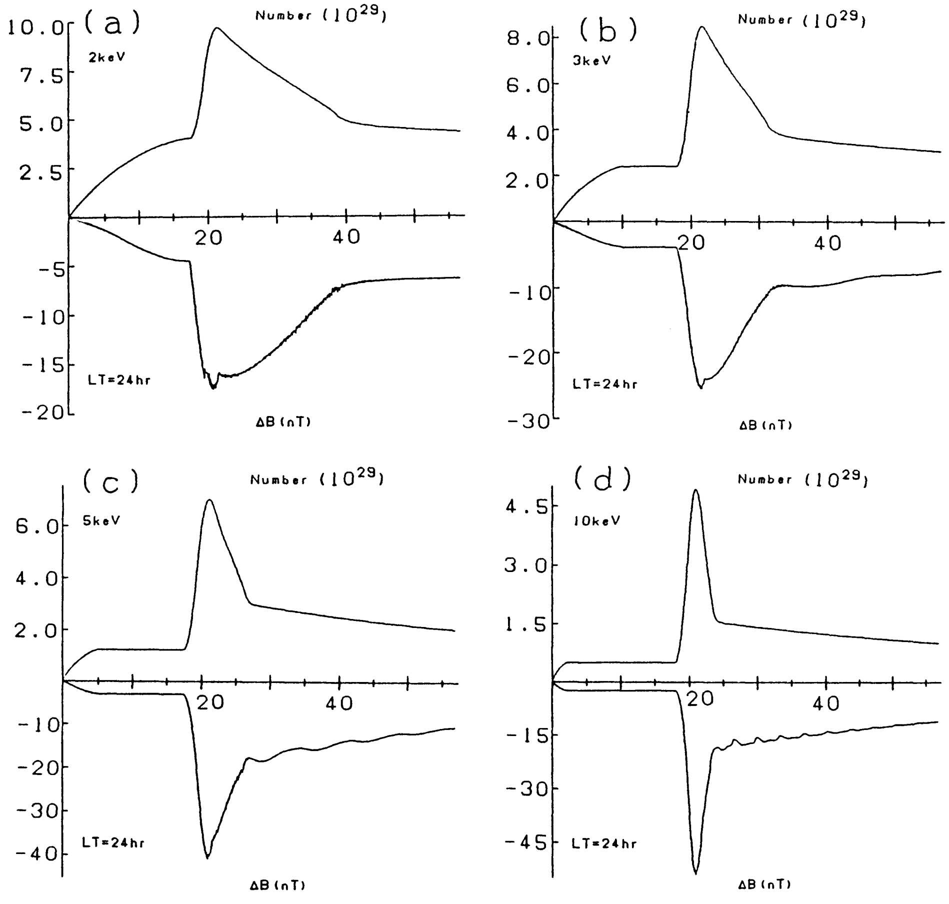

Fig. 3. Same as in Fig. 2, but in Mead and Fairfield's model.

distributed particle drifts around the earth and induces the decrease of ΔB. In the dipole field, the oscillation in ΔB is not induced since the gradient and curvature drifts are azimuthally symmetric (Fig. 2). On the other hand, in Mead and Fairfield's model, drift velocities and the radial distance of trajectories of drifting particles are not azimuthally symmetric. Thus the effect of the azimuthally anisotropic distribution on ΔB depends on local time and an oscillation of the ring current intensity is generated. The period of this oscillation corresponds to the time necessary for a proton to drift around the earth.

Although this oscillation may explain the second development of the *Dst* often observed during the recovery of storms after an impulsive southward IMF or in the impulse response function of the *Dst* to the IMF southward component, the following should be noted. Since our simulation is monochromatic (energy=2, 3, 5 or 10 keV and pitch angle=90° for each case), the anisotropy does not disperse. But for the actual ring current, some time later, the anisotropy disperses by energies and pitch angles and particles form a smooth ring current.

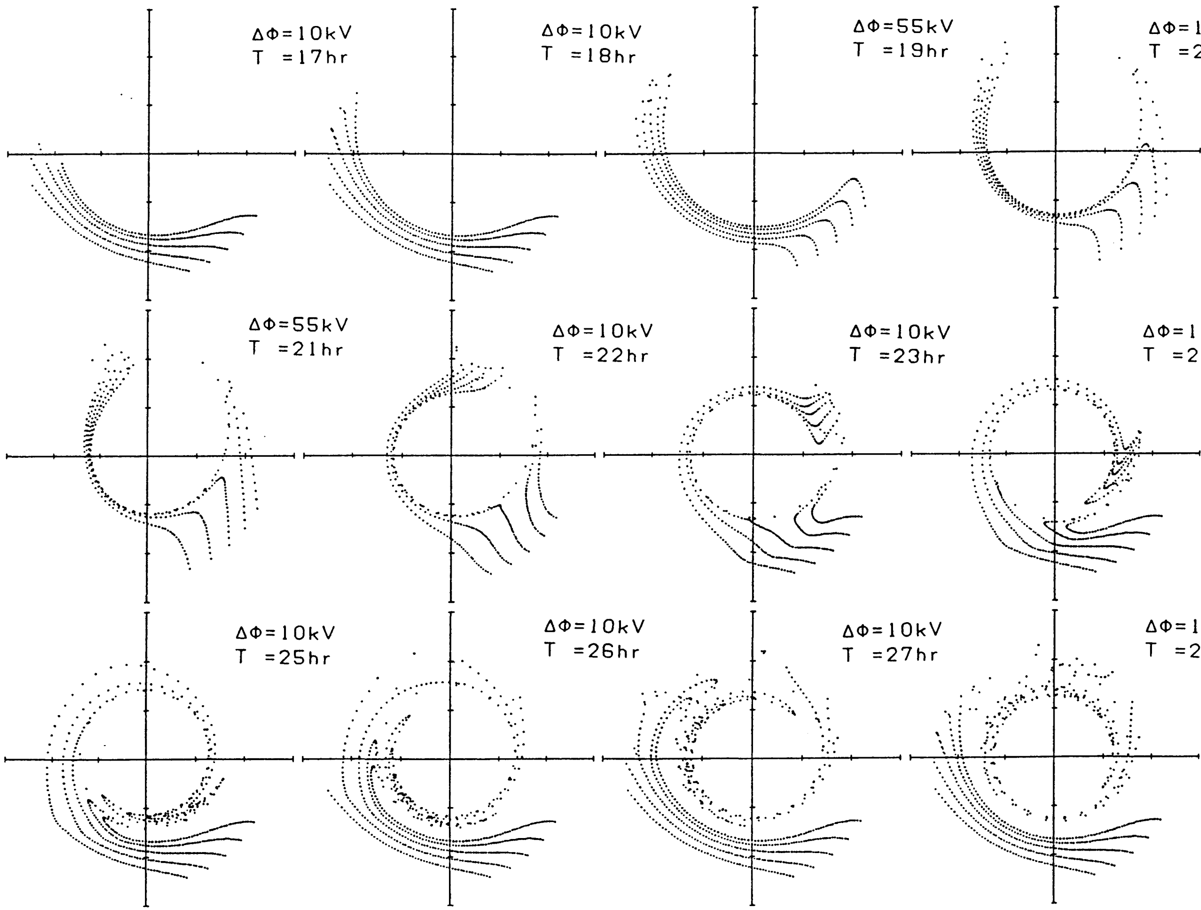

Fig. 4. Snap shots of particle (proton, 5 keV, 90°) distributions in the storm model. Horizontal and vertical axes represent east-west and sun-earth (upward is sunward) lines, respectively.

Finally, we should remark that the ring current is formed through the linear and nonlinear processes to the dawn-dusk electric field. Although the injection of particles and its magnetic effect may be approximated as a linear process, the trapping process (hence the resultant ring current intensity) may not be approximated as a linear process because it depends on the history of the $\Delta\Phi$. This effect will limit the efficiency of the linear prediction filter of the ring current from the solar wind parameters.

Computations were made by using the facilities of the Data Processing Center and the Data Analysis Center for Geomagnetism and Space Magnetism, both at Kyoto University.

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