

## RING CURRENT SIMULATION IN CONNECTION WITH INTERPLANETARY SPACE CONDITIONS

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**Abstract**—A ring current model has been obtained which permits calculations of  $D_{st}$  variations on the Earth's surface during magnetic storms. The changes in  $D_{st}$  are described by the equation

$$\frac{d}{dt} \bar{D}_{sto} = F(EM) - \frac{\bar{D}_{sto}}{\tau}$$

where  $\bar{D}_{sto} = D_{st} - bp^{1/2} + \tilde{c}$ ;  $p = mnv^2$  is solar wind pressure;  $F(EM)$  is the function, controlled by the electromagnetic parameters of interplanetary medium, of injection into ring current;  $\tau$  is the constant of ring current decay.  $\tilde{C} = C - \tau\varphi = 18$  nT, where  $C$  is the level of the  $D_{st}$ -variation field measurements;  $\varphi$  is the injection function characterizing the quasisteady-state injection of energy into the ring-current region. The constant  $\tilde{C}$  is determined from the condition that the change of the ring current energy from magnetic storm commencement to end should equal the difference between the injected and dissipated energy throughout the storm. The values of the factors  $b$  and  $\tau$  were found by the method of minimizing the sum of the quadratic deviations of the calculated  $D_{st}$  from the values observed throughout the storm:  $b = 0.23$  nT/(eV cm<sup>-3</sup>)<sup>1/2</sup>,  $\tau = 8.2$  h at  $D_{st} \geq -55$  nT and  $\tau = 5.8$  h at  $-120 \leq D_{st} \leq -55$  nT. The injection function  $F(EM)$  is of the form  $F(EM) = d(E_y - A)$  at the values of the azimuthal component of the solar wind electric field  $E_y > A$ , and  $F(EM) = 0$  at  $A \geq E_y$ ,  $d = -1.2 \times 10^{-3}$  nT s<sup>-1</sup> (mV/m)<sup>-1</sup> and  $A = -0.9$  mV m<sup>-1</sup>. Thus, the injection to ring current is possible at the northward  $B_z$  component of the IMF.

### 1. INTRODUCTION

The existence of the magnetospheric ring current and its relevance to geomagnetic field variations during magnetospheric storms have been confirmed by numerous experimental data and theoretical calculations (Akasofu and Chapman, 1972; Nishida, 1978). However, the energy sources and the mechanisms of plasma injection into the ring current have not been determined yet (Williams, 1981; Kamide, 1980). According to Rostoker and Falthammer (1967), Russell and McPherron (1973), Burton *et al.* (1975), Kamide (1980), Harel *et al.* (1981), Wolf *et al.* (1982), the supply of plasma to the ring current is due to penetration of the solar wind electric field  $E = V \times Bs$  ( $V$  is solar wind velocity,  $Bs$  is the southward ( $B_z < 0$ ) component of IMF) into the magnetosphere and subsequent plasma motion from the magnetotail plasma sheet to the ring current. According to Akasofu (1978), the supply of energy to the ring current is relevant to the function  $\varepsilon$  depending on the value of the Poynting vector in solar wind.

The ring current geomagnetic effect averaged over low-latitude observatories is described by the  $D_{st}$ -index after subtracting from the latter the magnetic field of currents on the magnetopause (Burton *et al.*, 1975)

$$DR = D_{sto} = D_{st} - bp^{1/2} + C \quad (1)$$

where  $p = nmV^2$  is the dynamic pressure of solar wind;  $b$  is a constant characterizing the relation between  $P$  and  $D_{st}$ ;  $C$  is the level of  $D_{st}$ -variation measurement on a given magnetically quiet day.

The relation of  $DR$  to the total energy of particles  $U_k$  in a closed magnetosphere and to the total energy of the Earth's magnetic field over the Earth's surface  $U_m$  is given by the following simple expression:

$$DR(\text{nT}) = B_0 \frac{2U_k}{3U_m} = 2.5 \cdot 10^{-21} U_k \text{ (erg)}$$

where  $B_0$  is the intensity of the Earth's magnetic field at the Equator (Dessler and Parker, 1959). If the  $D_{st}$ -index is used, the energy balance equation for the ring current takes the following form (Akasofu and Chapman, 1972;

Burton *et al.*, 1975; Akasofu, 1981a):

$$\frac{d}{dt} D_{sto} = F(EM) - \frac{D_{sto}}{\tau} \quad (2)$$

where  $D_{sto}$  is found from (1);  $F(EM)$  is the rate of energy supply to the ring current (the injection function) controlled by the electromagnetic parameters of interplanetary medium;  $\tau$  is a constant of ring current decay. The decay is assumed to follow an exponential law.

The  $D_{st}$ -variation was simulated at different injection functions  $F(EM)$  and values of the factors  $\tau$ ,  $b$ ,  $c$  by Burton *et al.* (1975), Akasofu (1981b), Bobrov (1981), Murayama (1982a, b).

It is known that in magnetically quiet periods the ring current fails to dissipate completely and that its magnetic effect ( $DR_0$ ) takes on the value  $-20$  nT  $> DR_0 > -40$  nT (Hoffman and Bracken, 1965; Schield, 1969; Porchkhidze and Feldstein, 1979). There should exist, therefore, an injection into the ring current  $\varphi_0$  which will balance its dissipation in quiet periods.

In this paper,  $D_{st}$  and  $DR$  are simulated on the basis of equation (2) with the following modifications compared with the earlier works:

(1) A constant injection to the ring current  $\varphi$  (such injection was designated  $\varphi_0$  above for the magnetically quiet periods) was included.

(2) A new form of the function  $F(EM)$  was determined at which the relation (2) permits  $D_{st}$  to be approximated to within a high accuracy.

(3) The decay constant  $\tau$  was assumed to be variable throughout a storm.

Allowance was made in the simulation for the requirement that the difference between the injected and dissipated energies throughout a storm should equal the ring current energy variation which was measured by the difference between the values of  $D_{st}$  prior to the commencement and immediately after a storm. The condition of the minimum value of  $\delta$ , the sum of the deviations of the calculated  $D_{st}$  from the observed values, was used as criterion of determination of the model parameters.

## 2. INITIAL DATA

We used the following solar wind parameters averaged over a 163 s interval: the velocity,  $V$  and density,  $n$ , of solar wind and the IMF component  $B_z$  inferred from the *Explorer-33* data. The observation results were kindly granted by WDC-A (principal investigators: in plasma J. Binsack, in IMF N. Ness). During two magnetic storms of February 1967 examined below, the interplanetary data were sufficiently comprehensive, and the values of the field and

the plasma parameters were interpolated to intervals of durations not exceeding 6 min.

The values of  $D_{st}$  were determined with a 2.5-min resolution from the magnetograms of 11 middle-latitude observations which were used in Burton *et al.* (1975) to find  $D_{st}$ . The geomagnetic field variations recorded on 31 January 1967 were taken to be the  $D_{st}$ -variation measurement level.

## 3. QUASISTEADY-STATE RING CURRENT

The ring current which satisfies the conditions

$$\frac{d}{dt} (D_{st} - bp^{1/2}) = 0; \quad F(EM) = 0;$$

$$AE < 100 \text{ nT}; \quad |D_{st}| \leq 10 \text{ nT} \quad (3)$$

during a period of at least 3–5 h will be called quiet quasisteady-state ring current. The conditions (3) are satisfied rather frequently. When they are realized, the ring current delay is obviously compensated by the injection whose nature differs from that adopted in Burton *et al.* (1975), Akasofu (1981b), Bobrov (1981) and Murayama (1982a, b). Let  $\varphi_0$  be the rate of energy supply to the quiet quasisteady-state ring current. The quiet ring current may be sustained by the corotation mechanism proposed by Lee *et al.* (1982). It is also possible that quasiviscous interaction gives rise to continuous plasma injection from the tail to the ring current region. In this case the convection intensity, hence the energy injected to the ring current, is a function of the solar wind plasma parameters  $V^2$  and  $nV^2$  (Afonina *et al.*, 1979; Levitin *et al.*, 1982). The analysis of the  $AE-C$ ,  $AE-D$  and  $S3-3$  measurements of the potential drop through polar cap (Reiff *et al.*, 1981) is also indicative of the existence of a constant potential component independent of the electromagnetic parameters of interplanetary medium. Such a component of the potential gives rise to continuous energy supply to magnetospheric region with closed force lines (Wolf *et al.*, 1982). Under magnetically quiet conditions,  $V$  and  $n$  in solar wind vary insignificantly and, therefore, the rate  $\varphi_0$  of energy supply to the quiet ring current may be considered, for a first approximation, to be constant. During magnetic disturbances,  $\varphi$  seems to vary, but its variations are inconsiderable compared with the variations of the function  $F(EM)$ . Therefore, the value of  $\varphi$  is taken below to be a constant. In such a case, the equation (2) will take the form

$$\frac{d}{dt} D_{sto} = F(EM) + \varphi - \frac{D_{sto}}{\tau}. \quad (4)$$

Let us introduce the designations

$$\tilde{C} = C - \varphi\tau; \quad \tilde{D}_{st0} = D_{st} - bp^{1/2} + \tilde{C}. \quad (5)$$

Then, the balance equation for the ring current will be of the form

$$\frac{d}{dt} \tilde{D}_{st0} = F(EM) - \frac{\tilde{D}_{st0}}{\tau}. \quad (6)$$

When (3) is satisfied, it follows from (6):

$$\tilde{D}_{st} = 0, \text{ i.e.} \quad (7)$$

$$D_{st} - bp^{1/2} + C = \varphi_0\tau. \quad (8)$$

Obviously,  $\varphi_0\tau = H_{rc}^q = DR_0$  and, therefore,

$$\tilde{C} = C - \varphi_0\tau = H_{mp}^q + H_{rc}^q - \varphi_0\tau = H_{mp}^q$$

i.e.  $\tilde{C}$  corresponds to the geomagnetic effect of the magnetopause currents when the conditions (3) are satisfied.

The value of  $\tilde{C}$  may be found in the following way. Let equation (6) be integrated over an interval equaling the storm duration  $(0, T)$ , and the expression of  $\tilde{D}_{st0}$  from (5) be substituted. Then,

$$\begin{aligned} (D_{st} - bp^{1/2}) \Big|_0^T &= \int_0^T F(EM) dt + T \left( \varphi - \frac{C}{\tau} \right) \\ &\quad - \frac{1}{\tau} \left[ \int_0^T D_{st} dt - b \int_0^T p^{1/2} dt \right]. \quad (9) \end{aligned}$$

The left part of (9), which represents the ring current energy variation, and all the integrals in the right part, which represent the difference between the injected and dissipated energies, may be calculated using the observation data at a given injection function  $F(EM)$ . It should be noted that, if  $\tau$  and  $\varphi$  are not constants throughout the storm, the value of  $\tilde{C}$  obtainable from (9) is an approximate estimate which was specified by minimizing the deviations of the calculated  $D_{st}$  from the observed values. The value of  $\tilde{C}$  may also be found from the solar wind parameters under quiet conditions ( $\tilde{C} = bp^{1/2} = H_{mp}^q$ ). Within the errors, the values of  $\tilde{C}$  determined by different methods coincide with each other and equal  $\tilde{C} = 18$  nT.

The magnetic effect of the quiet ring current may be found from ground-based observations of the Earth's magnetic field if the value of the  $D_{st}$ -index measurement level is known (the constant  $C$ ). If this level is considered to equal the external geomagnetic field discriminated in the main geomagnetic field (Cain, 1966) by spherical harmonic analysis ( $C = -20$  nT), then  $H_{rc}^q = DR_0 \approx -40$  nT; if, however,  $C = 0$ , then, according to the results of Feldstein and Porchkhidze (1983),  $H_{rc}^q = -20$  nT.

#### 4. THE FUNCTION $F(EM)$ OF ENERGY INJECTION INTO THE RING CURRENT DEPENDING ON THE ELECTROMAGNETIC PARAMETERS OF INTERPLANETARY MEDIUM

The function  $F(EM)$  was calculated on the following assumptions:

(1) On the Earth's surface the magnetic field from the magnetopause currents  $H_{mp}$  is proportional to solar wind pressure:  $H_{mp} = bp^{1/2}$  at  $100 \leq \sqrt{p} \leq 200$  (eV cm<sup>-3</sup>).

(2)  $H_{mp}$  is independent of  $\sqrt{p}$  at  $p < 10^4$  eV cm<sup>-3</sup>. Such an assumption has to be used to coordinate the observed and calculated  $D_{st}$  in the initial phase of the storm of 23–24 February 1967 and, probably, may be confirmed by the results obtained in Gosling *et al.* (1982).

Like Burton *et al.* (1975), we assumed that  $F(EM)$  was of the form

$$F(EM) \begin{cases} d(E - A) & \text{at } E > A \\ 0 & \text{at } A \geq E \end{cases} \quad (10)$$

where  $E$  is the solar wind electric field;  $d$  and  $A$  are constants.

The values of  $Q$ , the rate of  $D_{st}$  change considering the ring current decay (i.e. the rate of energy supply to the ring current), were calculated for each 25-min interval:

$$Q = \frac{d}{dt} (D_{st} - bp^{1/2}) + \frac{1}{\tau} (D_{st} - bp^{1/2}). \quad (11)$$

Figure 1a shows the mean-hourly values of  $Q$  as a function of  $E_y$  for the storm of 23–24 February 1967. Allowance was made for a 25-min delay of  $Q$  with respect to  $E_y$ . It was adopted that  $\tau = 8.2$  h at  $D_{st} > -55$  nT and  $\tau = 5.8$  h at  $D_{st} < -55$  nT. A linear dependence of  $Q$  on  $E_y$  can be seen at  $E_y > -0.4$  mV m<sup>-1</sup>. At the same time, the examination of the values of  $Q$  not averaged for each hour is indicative of a more accurate boundary of the linear dependence, namely  $E_y > -0.9$  mV m<sup>-1</sup>. The proportionality factor found by the method of least squares in the regression equation of the form  $Q = dE_y + \gamma$  at  $E_y > -0.4$  mV m<sup>-1</sup> is  $-1.2 \times 10^{-3}$  nT s<sup>-1</sup> (mV/m)<sup>-1</sup>. The functional form of the dependence of the rate of energy injection into the ring current on  $E_y$  is the same as that obtained by Burton *et al.* (1975) and does not confirm the results of Lee *et al.* (1982) who obtained on the basis of theoretical considerations that in the disturbed periods the rate of energy supply to the ring current is proportional to squared potential drop through polar cap, i.e. to  $E_y^2$ .

The data presented in Fig. 1a show a large spread of

$Q$  at the same values of  $E_y$ , outside the domain of the linear dependence of  $Q$  on  $E_y$ . Such a spread may be accounted for by various disregarded factors. In particular the contribution from the magnetic field of the field-aligned magnetospheric currents, which are

opposite in sign to the magnetic field of the DR-current, to the  $D_{st}$ -variation may prove to be significant in these intervals. A possible dependence of the function  $\varphi$  on solar wind parameters other than electromagnetic field is not excluded either; the injection and precipitation of particles as a result of the ionosphere-magnetosphere interaction is also possible. The sufficiently high values of  $Q$  in the periods with  $E \leq A$  indicate that the above discussed additional injection  $\varphi$  to the ring current took place during those intervals. The existence of such an additional injection at  $E_y < 0 \text{ mV m}^{-1}$  can also be seen in the experimental dependence of  $Q$  on  $E_y$ , found by Bobrov (1977).

Figure 1b shows the values of  $Q$  as a function of  $E_y$  for the storm of 7–8 February 1967. All the above discussed features of the storm of 23–24 February 1967 are observed also during this, more intensive, magnetic storm.

Thus, the ring current model is proposed which requires that but two parameters ( $\tau$  and  $b$ ) of six should be set independently. These parameters were determined by minimizing the sum of quadratic deviations of the calculated  $D_{st}$  from the observed values during the storm period ( $\delta$ ). The parameters  $\tilde{C}$ ,  $d$ ,  $A$  found from the relations (9), (10), (11) were also specified when minimizing  $\delta$ . The value of  $\delta$  can be much reduced if the parameter  $\tau$  characterizing the ring current decay intensity is assumed to be not constant but variable throughout a storm and dependent on  $D_{st}$ . The following values of the factors in (6) were inferred from the data on the storm of 23–24 February 1967:

$$\tau = \begin{cases} 8.2 \text{ h at } D_{st} > -55 \text{ nT} \\ 5.8 \text{ h at } D_{st} < -55 \text{ nT}, \end{cases}$$

$$b = 0.23 \text{ nT (eV/cm}^3)^{-1/2}, \quad d = -1.2 \times 10^{-3} \text{ nT s}^{-1} (\text{mV/m})^{-1}, \quad \tilde{C} = 18 \text{ nT}, \quad A = -0.9 \text{ mV m}^{-1}.$$

**5. COMPARISON BETWEEN THE OBSERVED AND CALCULATED VALUES OF  $D_{st}$**

Figure 2 presents the observed  $D_{st}^{\text{obs}}$  and the values of  $D_{st}^M$  calculated from (6) for the storm of 23–24 February 1967 at the values of the various factors indicated above. Allowance is made here and below for a 25-min delay of  $D_{st}$  relative to the solar wind parameters. The calculated and observed 2.5-min values of  $D_{st}$  were averaged over 1-h intervals to facilitate their plotting. An extremely good agreement between  $D_{st}^{\text{obs}}$  and  $D_{st}^M$  can be seen in all the phases of the storm. The sum of quadratic deviations for the 48-h values is  $\delta = 26 \text{ nT}$ .

The change of the value of  $A$  from  $A = -0.9 \text{ mV m}^{-1}$  to  $A = 0.5 \text{ mV m}^{-1}$  with preserving the values of all the

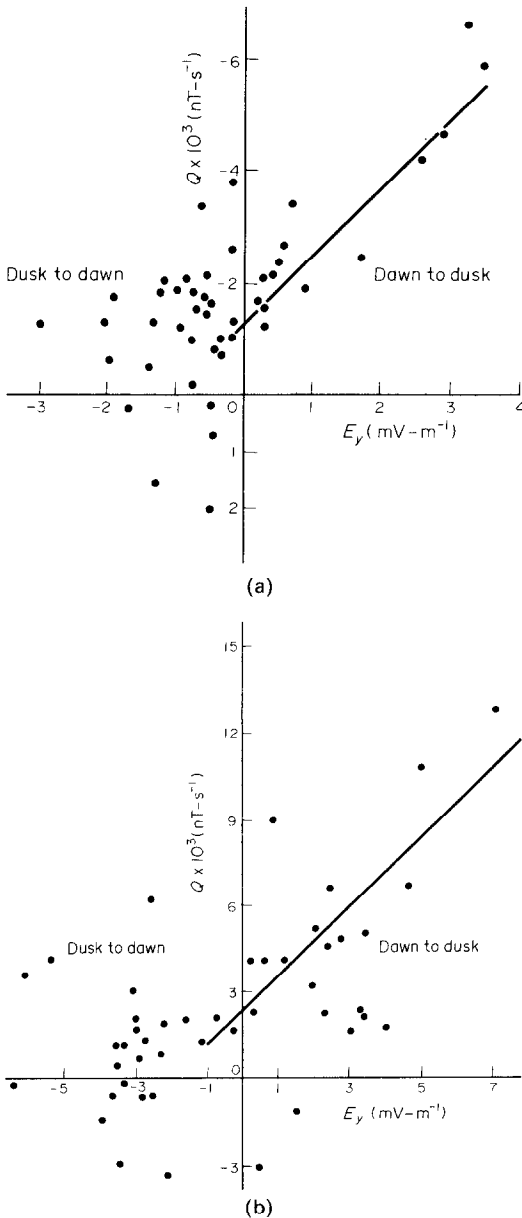


FIG. 1. INJECTION INTO THE RING CURRENT  $Q$  AT VARIOUS VALUES OF THE AZIMUTHAL COMPONENT ( $E_y$ ) OF ELECTRIC FIELD IN SOLAR WIND:  
 (a) THE MAGNETIC STORM OF 23–24 FEBRUARY 1967,  
 (b) THE MAGNETIC STORM OF 7–8 FEBRUARY 1967.

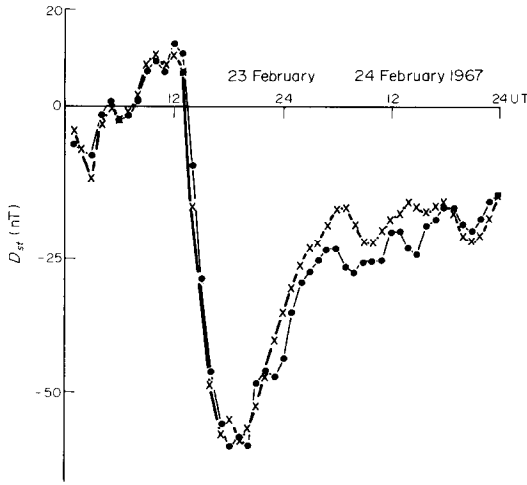


FIG. 2. THE OBSERVED  $D_{st}^{obs}$  (DOTS) AND MODEL-CALCULATED  $D_{st}^M$  (CROSSES) VALUES OF  $D_{st}$  FOR THE MAGNETIC STORM OF 23–24 FEBRUARY 1967.

rest factors gives rise to a significant increase of  $\delta$  and to a difference between  $D_{st}^{obs}$  and  $D_{st}^M$  during the storm recovery phase (see Fig. 3). Besides that, the recovery phase in the model  $D_{st}^M$  proves to be an absolutely “smooth” exponent, whereas relatively short-term variations are observed in  $D_{st}^{obs}$  during the exponential rise of the field in the recovery phase.

The proposed model was tested using the observed  $D_{st}$ -variation of the storm of 7–8 February 1967. From Fig. 4 it is seen that  $D_{st}^{obs}$  and  $D_{st}^M$  are in sufficiently good agreement;  $\delta = 58$  nT.

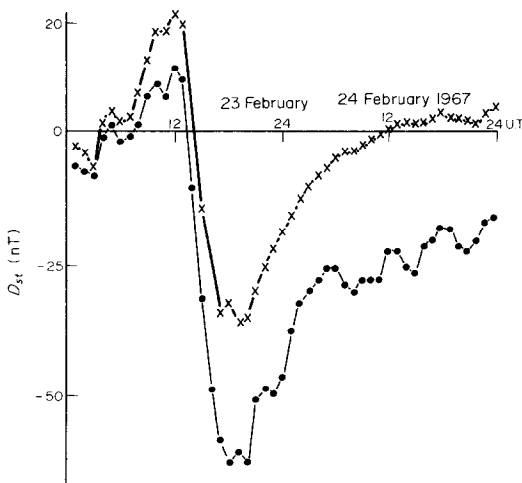


FIG. 3. THE SAME AS IN FIG. 2, BUT  $A = +0.5$  mV m<sup>-1</sup>.

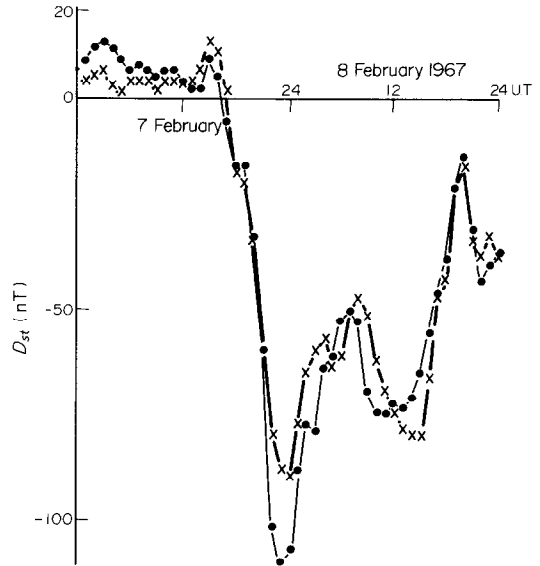


FIG. 4. THE OBSERVED  $D_{st}^{obs}$  (DOTS) AND MODEL-CALCULATED  $D_{st}^M$  (CROSSES) VALUES OF  $D_{st}$  FOR THE STORM OF 7–8 FEBRUARY 1967.

#### 6. ABOUT A POSSIBLE RELATIONSHIP OF ENERGY INJECTION INTO RING CURRENT TO SOLAR WIND VELOCITY

As was shown above, energy injection into ring current is permanent. According to the results of works by Afonina *et al.* (1979) and Levitin *et al.* (1982), the parameters  $V^2$  and  $nV^2$  may be responsible for the energy supply to the magnetosphere in the absence of an electric field directed from dawn to dusk. In this connection, the coefficients of correlation of  $Q$  with  $V^2$  and  $nV^2$  were calculated for the 1-h intervals in which  $E_y < -0.5$  mV m<sup>-1</sup> for the first storm and  $E_y < -0.9$  mV m<sup>-1</sup> for the second and  $Q < 0$  nT s<sup>-1</sup>. The regression lines for  $Q$  and  $V^2$  are presented in Figs. 5a and 5b for the storms of 23–24 and 7–8 February respectively. The corresponding regression equations are

$$Q = \left[ -0.08 \left( \frac{V}{100} \right)^2 + 0.03 \right] \times 10^{-3} \text{ nT s}^{-1}$$

$$Q = \left[ -0.15 \left( \frac{V}{100} \right)^2 + 0.81 \right] \times 10^{-3} \text{ nT s}^{-1}$$

at the correlation coefficients  $r = -0.4$  and  $r = -0.73$ . The coefficients of the correlation of  $Q$  with  $nV^2$  are  $\approx 0.1$ .

It can be seen from the plot presented, however, that the available data are still insufficient for accurate quantitative relations to be obtained. The relationships between the permanent energy injection into ring

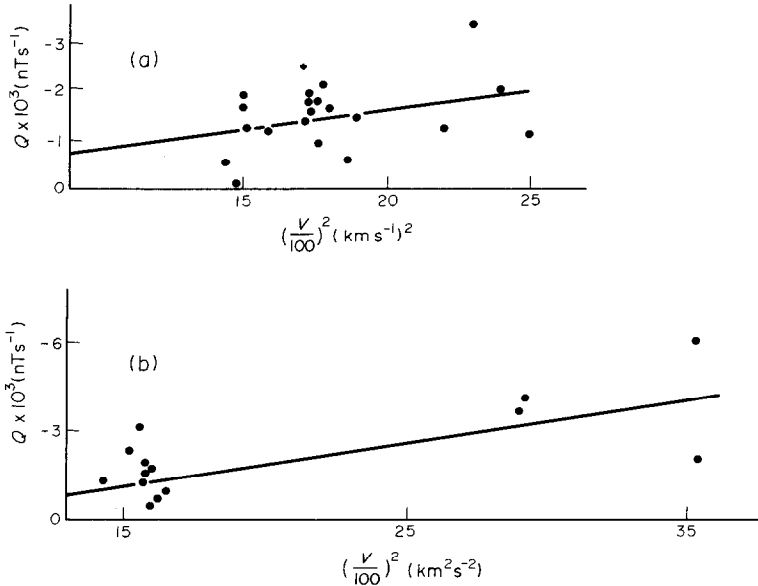


FIG. 5. INJECTION INTO THE RING CURRENT  $Q$  FOR THE SOLAR WIND ELECTRIC FIELDS FROM DUSK TO DAWN AS A FUNCTION OF SOLAR WIND VELOCITY: (a) THE STORM OF 23–24 FEBRUARY 1967, (b) THE STORM OF 7–8 FEBRUARY 1967.

current and solar wind parameters have still to be studied.

7. SOME REGULARITIES OF THE RING CURRENT DYNAMICS INFERRED FROM NUMERICAL SIMULATION

Here, we shall demonstrate the dependence of the ring current intensity on the conditions in interplanetary medium by making numerical simulation on the basis of equation (4).

The solution for (4) will be sought to be of the form

$$DR(t) = K(t) e^{-t/\tau} \tag{13}$$

at the initial condition

$$DR(t = 0) = DR_0.$$

After simple transformations we get:

$$DR(T) = \left\{ DR_0 + \int_0^T [F(EM) + \varphi] e^{t/\tau} dt \right\} e^{-T/\tau}. \tag{15}$$

Let us set now:

$$F(EM) = \beta_i \begin{cases} -4.35(E_{yi} + 0.9) \text{ nT h}^{-1} \\ 0 \end{cases} \begin{matrix} \text{at } E_{yi} > -0.9 \text{ mV m}^{-1} \\ \text{at } E_{yi} \leq -0.9 \text{ mV m}^{-1}. \end{matrix}$$

If  $F(EM) = \beta_i$  on the segment  $[t_i, t_{i+1}]$  of 1-h duration,

expression (15) gives the relation for calculating the hourly values of  $DR$ :

$$DR(t_{i+1}) = [DR(t_i) + (\beta_i + \varphi)\tau(e^{t_{i+1}/\tau} - e^{t_i/\tau})] e^{-(t_{i+1}-t_i)/\tau}. \tag{16}$$

The values of  $DR(t_{i+1})$  were calculated for  $\tau = 8.2$  h at  $DR \geq -85$  nT and  $\tau = 5.8$  h at  $-85$  nT  $> DR > -180$  nT and at invariable values of  $\varphi$  throughout the storm for  $\varphi = \varphi_0 = -2.4$  nT h<sup>-1</sup> and  $\varphi = \varphi_0 = -4.9$  nT h<sup>-1</sup>, which corresponds to  $DR_0 = -20$  and  $-40$  nT.

Figure 6 presents the given values of  $E_{yi}$  and the calculated  $DR$  at  $\varphi = -4.9$  nT h<sup>-1</sup>. Shown with the dashed line for comparison are the values of  $DR$  calculated at the same  $E_{yi}$ , but at  $\varphi = 0$  in the recovery phase.

It is seen that after the increase in  $E_y$  the ring current rises abruptly during 5 h. During the sixth hour, the dissipation processes got dominant over injection, so the  $DR$  recovery phase began. Considering the injection  $\varphi$ , the  $DR$  recovery is slower and stops as soon as  $DR = DR_0$ , whereas at  $\varphi = 0$  the recovery lasts up to  $DR = 0$ .

It is only natural that the determination of  $\tau$  from experimental data disregarding  $\varphi$  will give overestimated values of the decay constant. It is probably for this reason that Bobrov (1981) obtained somewhat overestimated values of  $\tau$ .

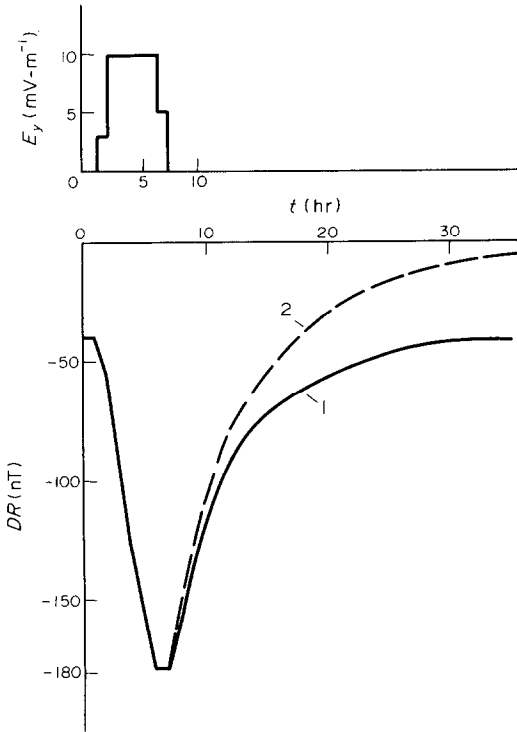


FIG. 6. VARIATIONS OF  $DR$  FOR THE  $E_y$  SEQUENCE SHOWN IN THE UPPER PART OF THE FIGURE FOR THE DECAY WITH A CONSTANT INJECTION  $\phi$ , THE SOLID LINE (1) AND WITHOUT INJECTION  $\phi$ , THE DASHED LINE (2);  $DR_0 = -40$  nT,  $\phi = -4.9$  nT h $^{-1}$ .

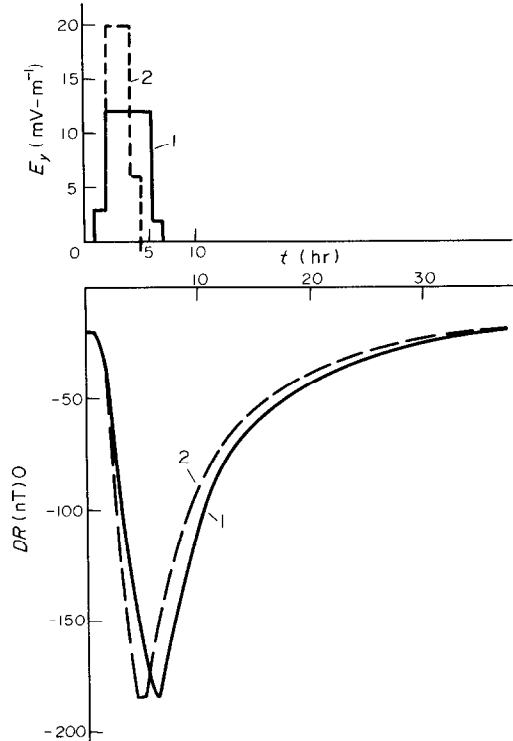


FIG. 7. VARIATIONS OF  $DR$  FOR TWO SEQUENCES OF  $E_y$  SHOWN IN THE UPPER PART OF THE FIGURE  $DR_0 = -20$  nT,  $\phi = -2.4$  nT h $^{-1}$ .

Figure 7 shows convincingly that the extremal intensity of  $DR$ -current depends not only on the extremal value of  $E_{yi}$  attained during the storm but also on the duration of the interval during which the electric field is sufficiently high in the dawn-dusk direction. From Figs. 6 and 7 it is seen that  $DR = DR_{\text{ext}} = -180$  nT may be attained at both the maximum  $E_y = 20$  mV m $^{-1}$  and the maximum  $E_y = 10$  mV m $^{-1}$ .

Let us estimate the maximum value of  $DR_{\text{max}}$  which will be observed at a given permanent injection at the moment when the rates of energy injection and dissipation in the ring current get equal ( $dR/dt = 0$ ):

$$DR_{\text{max}} = [F(EM) + \phi]\tau. \quad (17)$$

Figure 8 presents  $DR_{\text{max}}$  as a function of  $E_y$  at  $\phi = -4.9$  nT h $^{-1}$ . The bend of the straight line is due to the variations of  $\tau$  in different intervals of  $DR_{\text{max}}$ . The equation of the straight line in the plot for the interval  $-85$  nT  $>$   $DR_{\text{max}}$  (where  $\tau = 5.8$  h) is of the form

$$DR_{\text{max}} = -25.2 E_y - 51. \quad (18)$$

The relation (18) is close to the expression obtained earlier by Porchkhidze *et al.* (1976).

## 8. DISCUSSION OF RESULTS

(1) The concept has been introduced of quasisteady-state quiet ring current ( $DR_0$ ) which may be observed under relatively quiet geomagnetic conditions when the ring current decay is compensated for by a certain level of injection  $\phi_0$ . Such a quasisteady injection, which may vary during a storm, gives rise to the change of the

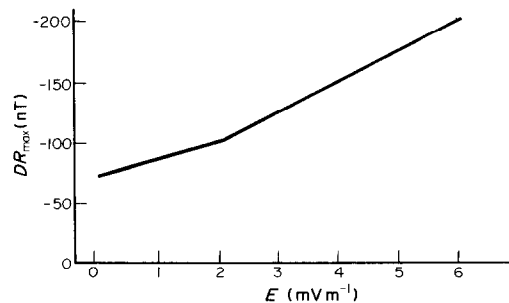


FIG. 8. THE MAXIMUM STEADY-STATE DECREASE  $DR_{\text{max}}$  OF THE GEOMAGNETIC FIELD ATTAINABLE AT VARIOUS VALUES OF THE AZIMUTHAL ELECTRIC FIELD COMPONENT  $E_y$  IN SOLAR WIND AT  $\phi = -4.9$  nT h $^{-1}$ .

constant in equation (6) by the value  $\tau\varphi_0$  ( $\tilde{C} = C - \tau\varphi_0$ ). This circumstance makes it possible to avoid the difficulties with which Burton *et al.* (1975) were faced when giving physical interpretation of the constant  $C$  in equation (2). The value of the constant  $C = 20$  nT adopted by Burton *et al.* (1975) corresponds to the quiet ring current on the Earth's surface  $DR_0 = H_{rc}^q = 5$  nT.

(2) The ring current model has been proposed which is of the form of an ordinary differential equation with a set of factors permitting the magnetic storms with explicitly expressed expansion phase to be sufficiently accurately described with a 2.5-min resolution. The correctness of determining the factors in equation (6) is confirmed by a good agreement between the calculated and observed values of  $D_{st}$  and by the fact that the simulation was made using the energy relation which states that the change of the ring current energy at the end and commencement of the storm should equal the difference between the energies supplied to and dissipating from the ring current. Obviously, this requirement must be satisfied in any model of the ring current. At the same time, from the data presented by Burton *et al.* (1975) it follows that their model fails to satisfy such an energy relation. If satisfaction of this relation is required and the values of the parameters  $\tau$ ,  $b$ ,  $d$ ,  $A$  adopted in Burton *et al.* (1975) are used, the factor  $C$  calculated from (9) will prove to be  $C = 38$ . Figure 9 presents the values of  $D_{st}^{obs}$  and  $D_{st}^M$  for the storm of 23–24 February 1967 calculated with  $\tau$ ,  $b$ ,  $d$ ,  $A$  from Burton *et al.* (1975) and  $C = 38$ . A good agreement between  $D_{st}^{obs}$

and  $D_{st}^M$  [which is better compared with Burton *et al.* (1975)] can be seen; the value of  $\delta = 31$  nT.

(3) The injection into the ring current has been shown to start at  $E_y = -0.9$  mV m<sup>-1</sup>, which corresponds to positive  $B_z$  equaling  $\sim 1.8$  nT at  $V = 500$  km s<sup>-1</sup>. The injection at  $B_z < 1.8$  nT seems to be due to the enhancement of magnetospheric convection. In fact, Hardy *et al.* (1981) have shown that the equatorial boundary of the region of diffusive electron precipitation, whose position is determined by the intensity of the large-scale magnetospheric convection, starts shifting monotonically to lower latitudes beginning from  $B_z = 1$  nT. This means that the plasma convection and supply to the ring current region commence not at  $B_z < -1$  nT [as was assumed by Burton *et al.* (1975)] but at  $B_z < \sim 1 \div 2$  nT.

(4) The conclusions about the parameters of the model are obtained under an assumption that the injection function into the ring-current is of a definite form. In particular, this function can be presented as a sum of two parts: the continuous injection  $\varphi$  and function  $F(EM)$ , depending linearly on electric field in solar wind  $E_y = B_z \cdot V$ .

It should be noted, that a choice of injection function is not unique. Again, as in the case of polar cap potential drop,  $\varphi + F(EM)$  can be defined by some other combination of the solar wind parameters. For example, Wygant *et al.* (1983) have shown that along with  $E_y = B_z \cdot V = B \cdot V \cos \theta$  the following combination may be used:

$$E_1 = B_T \cdot V \sin^4(\theta/2), \quad E_2 = B_T \cdot V \sin^2(\theta/2),$$

where  $B = \sqrt{(B_y^2 + B_z^2)}$ ,  $B_T$  = the magnetic field component transverse to the magnetopause and  $\theta$  = polar angle between transverse component of the IMF  $B$  and geomagnetic field at the magnetopause.

Any other form of injection function into the ring current will lead to a change of parameters set used in the ring current model. In particular, there will be no need of  $\varphi(V)$  term.  $E_1 \neq 0$  and  $E_2 \neq 0$  under any  $B_z$  direction if  $B_y \neq 0$ , that means a presence of continuous injection into the ring current, even at the northern direction of IMF  $B_z$  component. There will be no need of  $A$ -parameter, characterizing  $F(EM) \neq 0$  when  $E_y > A$ . Functional dependence of  $F(EM)$  on  $E_1$  or  $E_2$  suggests continuous injection under any direction of IMF  $B_z$  component.

The ring current models for other forms of injection function will be developed in future. At present it would be rather difficult to prefer some definite function of plasma injection into the ring current.

(5) The decay rate of the ring current has been shown to depend on its intensity and to vary as a magnetic storm develops. The data presented in Shevlin

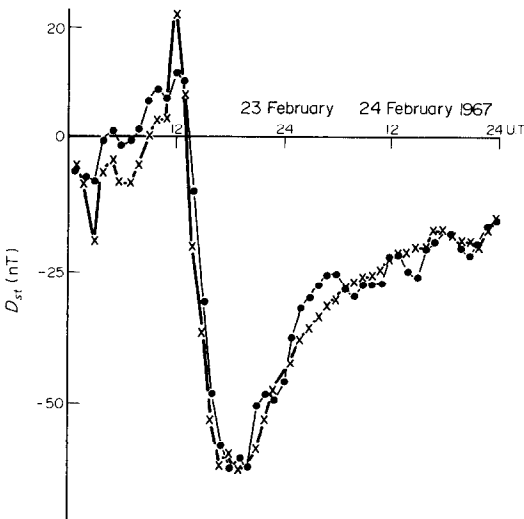


FIG. 9. THE OBSERVED  $D_{st}^{obs}$  (DOTS) AND CALCULATED IN TERMS OF THE MODEL OF BURTON *et al.* (1975) (CROSSES) VALUES OF  $D_{st}$  FOR THE STORM OF 23–24 FEBRUARY 1967. THE FACTOR  $C = 38$  nT IS ADOPTED TO REALIZE THE CONDITION OF ENERGY BALANCE DURING MAGNETIC STORM.



(1973a, b) and Zaitseva and Alekseeva (1976) show that the ring current decay time depends on its maximum intensity in a given storm, whereas it follows from the data presented by Akasofu (1981a) that the decay time depends on the value of the energy flux  $\varepsilon$  injected into the magnetosphere. According to Shevni (1973a, b) the ring current decay time increases, but according to Zaitseva and Alexeeva (1976) it decreases, with increasing  $D_{st}$  variation. In Shevni (1973a, b),  $t = 4.6$ ,  $\tau = -0.04 D_{st} + 1$ , which corresponds to  $\tau = 0.4$  h at  $D_{st} = -20$  nT and  $\tau = 1.1$  h at  $D_{st} = -100$  nT. Such small values of  $\tau$  and the character of the dependence of  $\tau$  on  $D_{st}$  are consequences of incorrect method for determining  $\tau$  used in Shevni (1973a, b). The method is based on erroneous concepts concerning the structure of magnetic disturbance field at low-latitude stations.

According to Akasofu (1981a),  $\tau$  may significantly vary throughout a storm and equal  $\tau = 20$  h at  $\varepsilon < 5 \times 10^{18}$  erg s $^{-1}$  and  $\tau = 1$  h at  $\varepsilon \geq 5 \times 10^{18}$  erg s $^{-1}$ . In the model proposed here, the decay time  $\tau = 8.2$  h at  $D_{st} \geq -55$  nT and  $\tau = 5.8$  h at  $-120 \leq D_{st} \leq -55$  nT and may vary or remain constant during the same disturbance depending on the value of  $D_{st}$ . In this case the constant of ring current decay  $\tau$  decreases with increasing  $|D_{st}|$ . Different values of  $\tau$  during the same storm may reflect both the variations of the ring current position inside the magnetosphere and the variations of the ring current ionic composition throughout the storm.

(6) The extremal values of  $DR_{\max}$  are determined in real magnetic storms by not only the electric field intensity in solar wind but also the duration of energy pumping onto the magnetosphere. The electric field intensity determines the extreme values of  $DR_{\max}$  which may only be attained at the appropriate values of  $E_y$  as a result of durable effect of electric field of a given intensity.

(7) If the permanent injection into ring current  $\varphi$  is disregarded, the values of the decay constant  $\tau$  inferred from experimental data will be overestimated.

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