RING CURRENT AND INTERPLANETARY MEDIUM PARAMETERS

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Resumen: El análisis de datos recientes sugiere que el escape de partículas de la mancha solar se produce en dos etapas: una en la atmósfera solar y otra en el espacio interestelar. Las partículas de alta energía son desviadas por el campo magnético solar y el campo magnético de las nubes interestelares. El estudio de datos recientes sugiere que el escape de partículas de alta energía es restrictivo y depende de la interacción con el medio interestelar.

Summary: Based on recent averaged data, the ring current decay parameter and the injection function associated with interplanetary medium parameters are analyzed. The distinction among the decay parameter values during a magnetic storm has been carefully drawn, the dependence of a on the injection function during the main phase and on the DS correlation during the recovery phase being emphasized. The modulated of the DS variation for weak and moderate storms as well as intensive storms carried out demonstrates a good agreement between the model time profiles and observed data of magnetic storm activity.

1. INTRODUCTION

The ring current is one of major magnetospheric sinks of the solar wind energy input into the magnetosphere. Its development is due to the trapped radiation. Trapped particles undergo the adiabatic drift around the Earth at the distance of 3 - 5 Earth's radii, where the geomagnetic field is a closed and parallel. The injection of the solar wind plasma into the magnetosphere as well as the precipitation of energetic ionospheric particles into the ring current occurs its spatial and temporal variability, and thereby, the occurrence of geomagnetic storms. These abrupt magnetic disturbances, as a consequence of the superposition of the ring current magnetic field on the Earth's surface and the dayside magnetic field, are of a global character. During the main phase of a magnetic storm, the geomagnetic field horizontal component decreases due to the decreasing ring current intensity. The field depression may reach hundreds of nT at the middle and low latitudes. It is followed gradually by the recovery phase of a geomagnetic storm, when the geomagnetic field returns to its previous level because of the loss of ring current particles. The growth rate and decay of the ring current reflect the energy balance in the solar wind - magnetosphere coupling.

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Variations of the ring current magnetic field observed at the Earth's surface are described by the energy balance relation as follows:

\[
\frac{dR}{dt} = F(t) - R(t)
\]

where \( R(t) \) is a geomagnetic activity index, \( b \) is a solar wind dynamic pressure, \( \beta \) is the coupling coefficient between a solar wind pressure and ground effects of currents on the magnetopause, \( \Delta CDF \) is the magnetic field of currents on the magnetopause under magnetically quiet conditions, \( F(t) \) is the injection function characterizing the energy input rate into the ring current, \( \tau \) is a parameter of ring current decay characteristic time \([1-4]\). The expression (1) has been analyzed on an hourly values time scale. The \( \Delta CDF \) values for each hour \( t \) are given in \([5]\), and interplanetary medium parameters necessary for the evaluation of \( \beta \), \( \Delta CDF \), and \( F(t) \) are given in \([6]\). Values of \( \Delta CDF \) were calculated for each month and the value of \( b \) was assumed to be constant and equal to \( 0.2 \times 10^{-6} \text{ erg cm}^{-2} \) [7].

The \( DR \) variation during a geomagnetic storm is defined by the relationship between \( F(t) \) and \( DR \). The relation \( |F(t)| > |\Delta CDF| \) is valid for the storm main phase, and \( |F(t)| < |\Delta CDF| \) for the recovery phase. As far as \( F(t) \) and \( DR \) are concerned, values of \( F(t) \) are associated with interplanetary medium parameters, and values of \( DR \) are related to intrinsic processes in the magnetosphere. Numerous studies have been carried out in order to define the relationship between the injection function \( F(t) \) and interplanetary parameters (see the brief review in \([7, 8]\)). It was found, on an hourly values time scale, \( F(t) \) depends on both (alleviated) components of the solar wind electric field and IMF magnitude standard deviation \([2, 9]\). There have been devoted numerous investigations to the parameter determination during different epochs of a geomagnetic storm (for the brief review in \([9]\)). Such an elevated interest is caused by the fact that the total energy dissipation rate \( \mathcal{U} \) inside the magnetosphere is to a considerable extent determined by the energy injection rate into the ring current related to \( \Delta CDF \), which in turn depends critically on the parameter \( t \) \([10, 11, 13]\). The results of such a comparison make it possible to spread the relation between the energy input into the magnetosphere and interplanetary medium parameters \([14]\).

Further progress in studying the relationship between the energy transferred into the magnetosphere and dissipation processes within it appears to be impossible without an accurate determination of the ring current decay parameter \([15]\). On the basis of hourly averaged data, there was carried out the further investigation of both the \( t \) parameter variations during different epochs of a geomagnetic storm and the injection function \( F(t) \), which describes the energy input rate into the ring current with respect to interplanetary conditions.
2.2. Modeling of the injection function

The injection function $F(t)$ has been shown to be dependent on the solar wind electric field azimuthal component [1, 2, 8, 9, 17] and also on the "viscous" friction between the solar wind and magnetosphere as well, which depends on the solar wind velocity [4, 8]. Then we have for $F(t)$:

$$F(t) = A_1 V - A_2 \tau + A_3 (V - 30) + A_4,$$

where $V$ is the solar wind velocity, $R_b$ is the IMF north-south component, $\sigma$ is the IMF magnitude variability, $A_1, A_2, A_3$ and $A_4$ are constants coefficients which have been determined by the method of stochastic approximation with adaptation [16].

In the model adopted, the $\tau$ parameter was assumed to be different during the geomagnetic storm episodes. The $\tau$ value during the main phase was considered to be constant as adopted in [17, 18]. During the recovery phase its value was considered to change freely with the ring current intensity. The method just mentioned was used to determine the $\tau$ parameter during the recovery, phase $\tau_{rec}$, under the assumption of the decay parameter during the main phase $\tau_{main}$, to be 4–9 h.

To choose the model parameters, there has been solved the problem of minimizing the functional of the quadratic mean between observed values of $D_R$ (denoted as $D_{R\text{mean}}$) and those calculated by means of the model treated (denoted as $D_{R\text{calc}}$). The number of variable used for minimizing ranged from 9 to 25. The solution of the optimization problem of such multidimensional type is always most complicated task because of computational difficulties. Another peculiarity of the problem tackled is of the kind that the fast converging method of the gradient type fail when applied to this case.

2.3. Method of stochastic approximation

The features mentioned above were decisive in choosing the stochastic approximation method with adaptation in order to select appropriate values of the model parameters.

The vector of parameters $U_{k+1}$ was calculated for the $(k+1)$th step as $U_{k+1} = U_k + \xi_k \epsilon_{k+1}$, where $k$ is the coordinate step vector, and $\xi_k$ is a vector of the random teaching process, which depends on the teaching vector $\epsilon_k$. Components of the $\xi_k$ vector were re-evaluated using formulae:

$$\xi_k = \beta_k \epsilon_k = \left(1 - \frac{1}{k} \right) \left(U_k - U_{k-1} \right),$$

where $\beta_k = \beta_{k+1} = 0$ is a value of the quadratic mean functional, and $\alpha, \beta, \delta$ are constant parameters accepted.

If the value of $\epsilon_k$ with $k$ increasing exceeded 1, the components were critically made less in their absolute value. The vector $\xi_k$ was calculated as: $\epsilon_k = \left(1 - \alpha \right) \epsilon_{k-1} + \psi_k$, where $\alpha$ is a random vector with coordinates uniformly distributed in the interval $[-1, 1]$. 

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Thus, a displacement vector $\mathbf{u}(\mathbf{x})$ has a determinate component at every step of the algorithm. The quicker this component increases the slower $I(U_0)$ decreases. At the same time, the stochastic component being present makes the method more flexible.

There have been carried out as many as 2000 to 5000 iterations under the assumption of different initial approximation parameters $U_0$ and various displacement steps $\alpha$. Finally, the obtained sets of optimal parameters of the DR model were compared. As a matter of fact, values obtained were close enough and the option of the best value of parameters analyzed was really time-consuming for a computer.

2.4. Determination of the $t$ parameter

The relationship $F = DR_{\text{max}}/t_{\text{mph}}$ is valid for the maximum depression of the ring current magnetic field. The $F$ value was calculated using Eq. (2), $F$ leading DR$_{\text{max}}$ by an hour. Then the $t_{\text{mph}}$ parameters have been determined for 45 geomagnetic storms, for which the difference between DR variations in the adjacent two hours around DR$_{\text{max}}$ is no more than 5%. It turned out the $t_{\text{mph}}$ value to depend dramatically on $F$, just as in [3, 19].

For the more accurate determination of coefficients in Eq. (2) during the ring current main phase, 96 geomagnetic storms were analyzed. There have been selected 227 two-hour intervals for which following conditions hold: $|\Delta B| < 2 \text{ nT}$, $\Delta / \gamma \leq 10 \text{ cm}^{-1}$, i.e. a DCF variation being less than 2 nT. Using the $t$ dependence on $F$, values of $F_{\text{mph}} = 5DR/(dt + DR)\gamma$ were calculated for the intervals chosen. Finally, values of $F_{\text{mph}}$ calculated have been compared with the injection function depending on the solar wind electric field azimuthal component defined as follows: $V(Bz)$, $V(Bz = 0.5e)$, $V(Bz = 0.66e)$, $V(Bz = -e)$. The relation $V(Bz = 0.66e)$, being defined as hour before of the DR variation, turned out to be the best among all those mentioned above. In fact, the azimuthal component, evaluated using this relation as hour ahead of the ring current DR variations, gives the closest correlation with $F_{\text{mph}}$. For an illustration, Fig. 1a, b show the dependence of $F_{\text{mph}}$ on $BzV$ (Fig. 1a) and $V(Bz = 0.66e)$ (Fig. 1b), correlation coefficients being $r = 0.81 \pm 0.05$ and $r = 0.88 \pm 0.04$, respectively.

During the injection period which corresponds to the main phase of a geomagnetic storm, the injection function $F_{\text{mph}}$ governed by interplanetary medium parameters, can be expressed by means of Eq. (2) with specified coefficients as follows:

$$F_{\text{mph}} = \frac{8.7 \times 10^{-7}V(Bz = 0.66e) - 14.1 \times 10^{-2}(V - 300) + 9.4}{8.6}$$

where $F_{\text{mph}}$ is in nT, $V$ is in km/s, $Bz$ and $e$ are in T. Figure 2 illustrates the relationship between $F_{\text{mph}}$ and $F_{\text{mph}}$ evaluated for 227 two-hour intervals mentioned above. The linear regression equation is shown graphically by the solid line, the correlation coefficient being equal to $0.88 \pm 0.05$.

The more accurate values of $F_{\text{mph}}$, obtained from Eq. (3), were used to calculate $t_{\text{mph}}$, once more. The $t_{\text{mph}}$ values were evaluated at the maximum ring current
Fig. 1. Relationship between $F_{\text{exp}}$, $-d\Phi/dt$, $d\Phi'$, and the solar wind electric field azimuthal component evaluated as $\Phi''(a)$ and $1/\Phi''(b)$, respectively, for 227 two-hour intervals during the injection period (the main phase) of a geomagnetic storm.
Fig. 2. Dependence of $F_{\text{cusp}}$, on $F_{\text{mod}}$, $F_{\text{mod}}$ being calculated using Eq. (13) with $\alpha$ how leading the corresponding variation of the ring current field.

Fig. 3. Variations of the parameter $\tau$ during the injection period (the main phase) of a magnetic storm. Values of $\tau$ have been determined for the epoch of maximum intensity of 45 magnetic storms, when values of $D$ for two adjacent hours at maximum differ by no more than 5% (crosses). The dependence of $\tau_{\text{cusp}}$ on $F_{\text{mod}}$ for small and moderate storms adopted in model calculations is expressed by the solid line.
magnetic field intensity $D\mu_{0}E_{\text{rms}}$ for 45 geomagnetic storms, with $F_{\text{rms}}$ leading $pR_{\text{rms}}$ (Fig. 3). The solid line expresses the dependence of $\tau_{\text{m},25}$ on $F_{\text{rms}}$ adopted for model calculations of geomagnetic field variations during magnetic storms. It has been recognized earlier [5, 10] that there exists a certain difference between $\tau_{\text{m},25}$ values for small and moderate storms as well as intense storms, adopted in the analysis so as not to include the storms with $|D\mu_{0}E_{\text{rms}}| \geq 160 \text{ nT}$ were chosen and values of $\tau_{\text{m},25} = = D\mu_{0}/(d \mu_{0}/dt)$ were calculated for adjacent two-hour intervals. There is shown the relationship between $\tau_{\text{m},25}$ and $F_{\text{rms}}$ (Fig. 4) for 120 two-hour intervals analysed.

\begin{align*}
\tau_{\text{m},25} \cdot \mu \text{ sec}
\end{align*}

$F_{\text{rms}} \cdot \mu \text{ Tm}$

![Graph](image)

Fig. 4. Variations of parameter $\tau$ due to $F_{\text{rms}}$ during the injection period of intensive magnetic storms. Values of $\tau$ were determined for the adjacent two-hour intervals using $F_{\text{rms}}$ calculated by means of Eq. (3) in hour ahead (around). The dependence of $\tau_{\text{m},25}$ on $F_{\text{rms}}$ for intensive magnetic storms adopted in model calculations is expressed by the solid line.

The $F_{\text{rms}}$ values were calculated using Eq. (3), with an hour ahead shift to the ring current magnetic field variations. The solid line in Fig. 4 expresses the dependence of $\tau_{\text{m},25}$ on $F_{\text{rms}}$ as assumed for the intensive storms modeling.

To divide a magnetic storm interval into the main phase (the injection period) and recovery phase (the decay period), we took into account the magnitude of the injection function. The portion of $F_{\text{rms}}$ depending on the solar wind velocity appears to be present continuously. Keeping this fact in mind, we obtain the following condition for all hourly averaged data during the storm injection period:

\begin{align*}
9.2 \times 10^{-8} \frac{V}{(2T_{\text{inj}} - 0.5T_{\text{inj}})} = 14.1 \times 10^{-7} (V - 300) + 7.4 < -1.5 \times 10^{-7} (V - 300),
\end{align*}

or

\begin{align*}
V/2T_{\text{inj}} < -1146,
\end{align*}

when the electromagnetic injection exceeds the viscous one. The remaining portion of a geomagnetic storm is attributed to the decay period in spite of the injection process into the ring current continues to proceed with the intensity:

\begin{align*}
-14.1 \times 10^{-7} (V - 300) \text{ under the condition } V > 300 \text{ km/s}.
\end{align*}

As far as the parameter $\tau_{25}$, during the decay period (the recovery phase) is concerned, its values have been determined by the stochastic optimization method.
mentioned above. For weak and moderate storms, \( \tau_{\text{ph}} \) increases when \( DR \) decreases, being ranged as follows:

\[
\tau_{\text{ph}} = \begin{cases} 
5.4 h, & \text{if } -150 \leq DR \leq -170 nT \\
9.1 h, & \text{if } -30 \leq DR \leq -50 nT 
\end{cases}
\]

For intensive storms, the \( \tau_{\text{ph}} \) values appear to be slightly dependent on \( DR \), being ranged as follows:

\[
\tau_{\text{ph}} = \begin{cases} 
10.8 h, & \text{if } DR = -300 nT \\
7.0 h, & \text{if } DR = -30 nT 
\end{cases}
\]

The detailed pattern of \( \tau_{\text{ph}} \) variations can be found in Tab. 1. The \( \tau_{\text{ph}} \) values for intensive storms were calculated using 124 adjacent two-hour intervals. The scatter of values is quite considerable. But the corresponding median values are close to the \( \tau_{\text{ph}} \) dependent on \( DR \) as presented in Tab. 1. All results of the \( \tau_{\text{ph}} \) dependence on the injection function and \( F \) during the injection period; the main phase, and \( \tau_{\text{ph}} \), depending on \( DR \) during the decay period (the recovery phase).

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Table 1. Ring current decay parameters for magnetic storms of the different intensity: \( \tau^{\text{ph}}_{\text{magn}} \) dependent on the injection function \( F \) during the injection period; the main phase \( \tau_{\text{ph}} \), depending on \( DR \) during the decay period (the recovery phase).
3. COMPARISON OF STUDIES ON THE RING CURRENT MAGNETIC FIELD MODELING

3.1. Injection function

It is of interest to compare the injection function suggested with those adopted earlier. The structure of the injection function reflects its duality: it is controlled by processes of reconnection of the interplanetary and geomagnetic fields (which is manifested by the dependence on both the IMF north-south component \( B_z \) and the IMF magnitude variability \( r \)), and by viscous interaction between the solar wind and magnetosphere as well (which is manifested by the portion dependent on the solar wind velocity \( V_s \)). The injection into the ring current due to processes of reconnection has widely been discussed [1, 4, 7–9 and references therein]. The essential difference between Eq. (3) for the injection function and those given by other authors is just the presence of the additional injection due to the viscous interaction. In fact, the injection does not become zero during the northward IMF \( B_z \) component orientation, but some additional portion of the energy flux, dependent on the solar wind velocity, persists, increasing when \( V_s \) increases. Such an injection was already reported in [4]. It has been shown the injection function model to increase by 3–5 nT/h due to the solar wind velocity enhancement from 300 km/s to 400 km/s.

There should be expected the decrease of the geomagnetic field level at the low-latitude observatories during the increased solar wind velocity as a direct result of viscous injection. Such a decrease was actually revealed during the night hours on the magnetically quiet days at several magnetic observatories in India [20]. The geomagnetic field level decreases by 10 nT as \( V_s \) increases by 100 km/h, the correlation coefficient being equal to \(-0.6\). The decrease of the DI variation field by \(-10\ nT\), caused by the solar wind velocity changing \( \Delta V_s = 100\ km/s\), has been revealed in intervals when the Earth meets high velocity solar wind streams [21]. The tendency of the horizontal component to decrease has been observed at the Kakioka observatory during 22 magnetically quiet days with \( DI > 0\) under the condition of increasing solar wind velocity. In spite of quite large scatter of values, the increasing of the solar wind velocity by 100 km/s appears to cause the horizontal component decreasing by \(5 \sim 10\ nT\). The magnitude of decreases varies from year to year, and \( DI \) is even 10 nT at the equator, 9 being a geomagnetic latitude.

The ring current magnetic field decreases appear to be obvious when the Earth meets high velocity solar wind streams. Figure 5 shows hourly averaged values of \( DI \) evaluated during the \( \pm 5 \) h long intervals with high velocity solar wind streams and the IMF \( B_z \) component exceeding 2 nT. There were analysed 36 such intervals chosen during the period of 1967–1970 [25]. The correlation coefficient between \( DI \) and \( V_s \) is \(-0.55\). According to the regression equation the solar wind velocity change \( \Delta V_s = 400\ km/s\) causes \( \Delta DI \sim 15\ nT\).

The portion of the injection function in (3) defining the viscous injection, is quite
coincident with the magnetic field decreases at low-latitude observatories mentioned above. As a matter of fact, $\Delta F = -141 \times 10^{-3}$ nT/h if $\Delta V = 190 \text{ km/s}$. This corresponds to $|\Delta R| = 15 \text{ nT}$ for quasi-stationary conditions if $\tau = 9 \text{ h}$ is adopted. The viscous injection plays an important role in the ring current feeding during a final portion of the recovery phase. The best agreement between the observed ring current field and field values evaluated by DR modeling was obtained for $A_k = -144 \times 10^{-3} \text{ nT/h km s}^{-1}$, namely, is swept in (i).

![Dependence of $DR = D_R - \bar{\beta} \sqrt{\beta + DCF}$ on the solar wind velocity $V$ when the Earth meets high velocity streams with the IMF north-south component $B_z > 0$.](image)

The electromagnetic portion of the injection function together with the constant term (see Eq. (3)) quite likely has the structure suggested in [9], although the values of coefficients are distinctly different. $\bar{\beta}$ is caused by the different way of calculating $F_{max}$. To calculate $F_{max}$ using data of 44 two-hour intervals, $\tau_{m,sh}$ was assumed to be constant and equal to 6 h [9]. On the contrary, to calculate $F_{max}$ used to determine the coefficients $\beta$ in (3), the dependence of $\tau_{m,sh}$ vs. $F_{max}$ (Fig. 3) was taken into account.

### 3.2 Decay parameter

In this paper as in [3, 8, 10, 19], the parameter $\tau$, which defines the particle dissipation rate for the ring current, is assumed to be different during the main phase (the injection period) and during the recovery phase (the decay period) of a geomagnetic storm. The $\tau_{m,sh}$ variations due to $F_{max}$ are shown in Fig. 6. We can compare the relationship analyzed for both weak and moderate (1) and intensive (2) storms. The value of $\tau_{m,sh}$ adopted in [19] is also shown (3). For large values of the injection function, the value of $\tau_{m,sh}$ drops down to 1-7 h or 2-6 h, which does not coincide with the value of 3 h according to [10]. In the range of the most frequent $F_{max}$ values ($-20 \pm -80 \text{ nT/h}$), the $\tau_{m,sh}$ value adopted in [10] falls just between the curves (1) and (2) associated with storms of the different intensity. For the large $F_{max}$ values,
we can see (Fig. 6) the decay parameter not to fall down to the value of 1 h or even less as claimed in [3]. Actually, such an abrupt decay $\tau < 1$ h means an enormously large energy injection rate into the ring current [24].

The assumption of $\tau_{\text{min}}$ to be dependent on the ring current magnetic field variations was adopted in [8, 10]. This dependence of $\tau_{\text{min}}$ on $I_R$ is statistically equivalent to the dependence of $\tau_{\text{min}}$ on $I_R$ which is strongly dependent on the solar wind electric field azimuthal component. In fact, there exists a distinct relation-
Figure 2: The decay parameter during a magnetic storm main phase in terms of DR according to [19] — a solid line with crosses, [9] — a dashed line with crosses, and [10] — a dashed line.

The Fmax deflection was recalculated using Eq. (4).
The determination of $\tau_{\text{obs}}$ makes some difficulties discussed in detail in [10]. There are some discrepancies as far as the dependence of $\tau_{\text{obs}}$ on $DR$ is concerned. According to [9, 17, 18], the increasing of $\tau_{\text{obs}}$ due to the $|DR|$ growth is evident. The increasing of $\tau_{\text{obs}}$, caused by decreasing $|DR|$ has also been reported [8, 10]. In our opinion, the increasing of $\tau_{\text{obs}}$ due to the $|DR|$ decreasing during individual storms seems to be more natural as it reflects a faster loss of short-lived particles, i.e. the ring current destruction which begins from its innermost shells around the Earth. At the same time, different types of storms are characterized by specific dependences of $\tau_{\text{obs}}$ on $DR$. The $\tau_{\text{obs}}$ values for intensive storms exceed essentially those for weak and moderate storms as can be seen in the Tab. 1. The expressions for the $\tau_{\text{obs}}$ dependence on $DR_{\text{max}}$ defining the maximum depression of the geomagnetic field during the main phase have been found [9, 17, 18, 19]. The amount of points, used to obtain the statistical linear relationship between $\tau_{\text{obs}}$ and $DR_{\text{max}}$, was limited and rather scattered. For this reason, there is no surprise that a slight change in the way of selecting magnetically quiet intervals during the storm recovery phase has caused the essential change in the relation analyzed. According to [17, 19] we have for example:

Fig. 9. Dependence of $\tau_{\text{obs}}$ on $DR_{\text{max}}$ according to [17] (curves). Dots correspond to the same values of $\tau_{\text{obs}}$($DR$) after IMF northward turnings.
The relation of $\tau_{\text{r},\text{inj}}$ to $D_{\text{max}}$ (crosses) evaluated [17, 19] for 13 geomagnetic storms during intervals with $B_z > 0$ and $\sigma \leq [B_z]$ is shown in Fig. 9. To calculate $\tau_{\text{r},\text{inj}}$ by the BR modeling, the $D_R$ values after the end of the injection in the ring current were used instead of $D_{\text{max}}$ [9, 19]. In such a case, the values of $D_R$ and $D_{\text{max}}$ sometimes differ dramatically. In Fig. 9, the same values of $\tau_{\text{r},\text{inj}}$ and corresponding $D_R$ values for the very high of the IMF northward turning are presented by dots. The tendency of $\tau_{\text{r},\text{inj}}$ to increase as $D_R$ increases becomes less distinct in this case. The scatter of dots becomes expressive, the regression line slope being increased by 1.5 times.

4. MODELLING OF $\alpha$ VARIATIONS

To calculate the ring current magnetic field variations the algorithm was constructed on the basis of the previous analysis using the reciprocity relationship:

$$D_{\text{R}}(t) = (D_R(t - \tau_{\text{r},\text{inj}}) - D_R(t - \tau_{\text{r},\text{inj}})) / (2 - \tau_{\text{r},\text{inj}}),$$

where the injection function $F_{\text{inj}}$ was evaluated as follows:

$$F_{\text{inj}} = \begin{cases} \frac{8.2 \times 10^{-4} [B_z - 0.67 \gamma] - 14.1 \times 10^{-2} [V - 300] + 8.4}{10^{-2} [B_z - 0.67 \gamma]} < -1146 \quad \text{(the injection period)}, \\ -14.1 \times 10^{-2} [V - 360] \\ \text{if } V [B_z - 0.67 \gamma] > -1146 \quad \text{(the decay period)}, \end{cases}$$

where the IMF magnitude standard deviation $\sigma_{\text{B}}$ is:

$$\sigma_{\text{B}} = \begin{cases} \sigma, & \text{if } \sigma \geq 6 \text{ nT}, \\ 0, & \text{if } \sigma < 6 \text{ nT}. \end{cases}$$

The expression for determining the injection function is the same for all storms regardless of their intensity. The separate values of the decay parameter $\tau$ were adopted for the main and recovery phases, $\tau_{\text{r},\text{inj}}$ being considered in terms of $F$ during the injection period and $\tau_{\text{r},\text{inj}}$ being considered in terms of $D_R$ during the decay period. The values of $\tau$ for weak and/or moderate storms ($D_{\text{max}} \leq -150 \div -160$ nT) and intensive storms ($D_{\text{max}} > -150 \div -160$ nT) were used as given in Tab. 1.

The $D_{\text{max}}$ values evaluated for 50 selected intervals were calculated using the algorithm mentioned above. The intervals were selected during the period of 1967–1980 under the condition of the field decreases to be by 45% or more. The $D_{\text{max}}$ values calculated were compared with observed ring current magnetic field variations $D_{\text{max}}$.

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It is worthwhile to note that the mean hourly value standard deviation of $\Delta R_{\text{mod}}$ relative to $\Delta R_{\text{rep}}$ is 14 nT for the whole amount of data analysed (3352 hours). The $\Delta R_{\text{rep}}$ (observed ring current activity data) and $\Delta R_{\text{mod}}$ (model ring current magnetic field variations) time profiles are plotted in Fig. 10 for comparison. Three intensive (Fig. 10, a–c) and three moderate storms (Fig. 10, d–f) were chosen for the illustration. Correlation coefficients $r$ between $\Delta R_{\text{rep}}$ and $\Delta R_{\text{mod}}$ as well as mean square deviations $\sigma$ referred to an hourly value in the interval analysed are given in Fig. 10 for all storms illustrated. A good agreement between the model time profiles and observed field variations is clearly seen.

Fig. 10a. Modeling of the $\Delta R$ variation for the August 27–30, 1978 magnetic storm.
5. DISCUSSION AND CONCLUSION

The successful modeling of the ring current magnetic field variations infers the necessity to analyze properly the energy injection rate into the ring current, associated with interplanetary medium parameters. The injection is assumed to carry out in two principal ways. Processes associated with the viscous interaction of the solar wind and the magnetosphere are controlled by the solar wind velocity. On the other hand, processes of reconnection of the interplanetary and geomagnetic fields are controlled by the IMF north-south component $B_z < 0$ and the IMF magnitude variability. Such versatility of governing parameters makes difficulties as to an adequate identification of the injection function. Moreover, the ring current decay parameter is used to be different during a geomagnetic storm, its values being specific for the main and recovery phases. Finally, decay parameter values during the injection period (the main phase) are controlled by the injection function and its values during the decay period (the recovery phase) are governed by the ring current magnetic field variations. From the viewpoint of physical processes taking place in the ring current belt, the character of the $\tau$ parameter variations during different storm phases reflects...
Fig. 10d. As for Fig. 10a but for the January 7-9, 1979 magnetic storm.

Fig. 10e. As Fig. 10a but for the February 7-10, 1967 magnetic storm.
the fundamental difference in the plasma loss processes. These processes are much faster during the storm main phase than during the recovery phase, the decay parameter being smaller during the injection period. It means that just trapped particles are detained in the geomagnetic field for a shorter time than particles which have not escaped during few hours. Furthermore, the decay parameter $\tau$ is different for weak

April 18-19, 1974

$s = 10.0 \text{ nT}$
$\tau = 0.88$

Fig. 10f. As for Fig. 10a but for the April 18-19, 1974 magnetic storm.

and/or moderate storms as well as intensive storms. This fact is partly caused by the ring current location in the magnetosphere. However, the main reasons for this difference are both the fluctuations of the chemical composition as to ring current ions and their varying energetic characteristics. The slower ring current decay process during the recovery phase of intensive storms testifies such association.
Taking into account the decay parameter's distinction for different phases of a geomagnetic storm and the dependence of the injection function on interplanetary parameters, the algorithm was constructed for the modeling of ring current magnetic field variations. The observed ring current activity and model time profiles reveal a good agreement for both weak and moderate storms and intensive storms. Therefore, we may consider the results obtained as further evidence for the adequate identification and accurate understanding of the solar wind–magnetosphere coupling mechanism.

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