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RING CURRENT DECAY TIME IN MODEL WITH IONOSPHERIC ELECTRIC FIELD SATURATION

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[1] We calculated the DR-current decay time τ_T with steps 5 minutes using the 20 Nov 2003 superstorm data. We applied the Dessler-Parker-Skopke equation (DPS) and the *SYM-H* indices. Unlike the traditional approaches, we defined the value Q_{DR} - DR-current power - from the relation $Q_{DR=}0.5$ (ε *-Q_i) where power Q_i dissipated in the ionosphere, and the input power (Poynting flux) ε* are defined with the effect of the ionospheric electric field saturation taken into account. Such an approach differs from the known in the literature where they calculate Q_{DR} through the DPS equation, and use the magnetospheric Poynting flux, calculated according to the model by Perreault-Akasofu [1978] (ε_A), or Mishin et al. [2000] (ε'), instead of ε*.
The τ_T values were compared with theτ_G and τ_O values calculated by the two basic known empirical models, Gonzalez et al. [1989] and O'Brien and McPherron [2000], respectively. The τ_T time varies over the superstorm from ~20 minutes in the main phase to ~4 hours at the onset of the recovery phase, and is correlated with the observed changes of the superstorm's seven regimes detected earlier. At the main phase the τ_T values are close to τ_G, and at the recovery stage they are close to the τ_O values. The τ_T values in the storm main phase are manifolds or by an order of magnitude lower than the corresponding τ_O values. Unlike τ_T, the changes of τ_G and τ_O over the superstorm (especially τ_O), do not correlate with the observed dramatic changes of the superstorm's regimes. Mean-square spread of the calculated values τ_T is considerably lower than in the previous papers of where we used ε_A or ε' instead of ε*.
In general, the new method application provided, for the first time, the τ scale which takes into account, though only qualitatively, 7 various regimes of magnetospheric disturbance. We noted the causes of those distinctions.

1. Introduction

[2] The ring current τ decay time is one of the basic parameters for magnetosphere energetics. There are two known main empirical models of τ changes during a storm. In Model 1, $\tau=\tau_O$ is the function of the solar wind electric field $E_{sw}=V_{sw}B_{sw}$ [O'Brien et al., 2000]. In Model 2 the function $\tau=\tau_G$ of the SYM-H ring current intensity is used [Gonzalez et al., 1989]. In Model 1 values τ_O lie within 4 to 20 hours. In Model 2, for the substorm main phase, the τ_G values are much lower: $0.25\leq\tau_G\leq4$ hours. Model 1, by definition, does not take into account the effect on τ of the processes inside the magnetosphere and, consequently, *substorms* Model 2, in its turn, disregard the dual nature of ring current which is regulated by both substorm processes and solar wind.

[3] We should note, that the authors of many papers [e.g., Baker et al. 1995, 1997; Lu et al. 1998, 2001; Ostgard et al., 2002; Tanskanen et al., 2002], applying the DPS equation to estimate the relation between τ and Q_{DR} in the storm main phase, set τ the decay constant, defined using the data, containing all the three phases of a storm - initial, main and recovery phase. Such a method, prevailing in the literature, results in τ values which are overestimated by an order of magnitude when applied for the main phase. It follows from the fact, that the third phase (recovery) has a decisive significance in the initial data base. In particular, when calculating Q_{DR}, the above mentioned authors concluded that the input energy transported into the magnetosphere is consumed more in the ionosphere than in the DR ring current. This conclusion was obtained by the DPS equation in which $\tau\geq4$ hours was accepted, which is by an order of magnitude more than the τ values calculated by other methods [Akasofu, 1981; Gonzalez et al., 1994; Mishin et al., 1998; Karavaev et al., 2006; 2008].

[4] In this paper we apply a new approach which is tested using the data for the 20 Nov 2003 (02-24) UT superstorm. The DR-current decay time, $\tau=\tau_T$, is calculated as the function of the Poynting input flux, $\varepsilon = \varepsilon$ * and the power Q_i dissipated in the ionosphere and driven by the substorm processes (see Section 4). We supposed $\varepsilon^*=(\Psi_1\cdot\langle B_L\rangle\cdot V_{SW})/\mu_0$, where $\langle B_L\rangle$ is a average magnetic field and Ψ_1 is an open magnetic flux in the tail's two lobes [Kuzminykh et al., this Seminar]. Earlier, the authors of this paper applied models $\varepsilon = \varepsilon_A$, or $\varepsilon=\varepsilon'$, where $\varepsilon_A = (4\pi/\mu_0)\cdot V_{SW}\cdot B^2\cdot\sin^4(\theta/2)\cdot l^2$ [Perreault and Akasofu, 1978], or $\varepsilon'=(\Psi_1^2\cdot V_{SW})/(\mu_0\cdot S_T)$ [Mishin 1990]. Here $\mu_0=4\pi\cdot10^{-7}$, V_{SW} the solar wind velocity, $B=(B_y^2+B_z^2)^{1/2}$, $\theta=\mathrm{arctg}(B_y/B_z)$, B_y and B_z are the components of IMF, $l=7R_E$.

[5] The Ψ_1 values, generally speaking, are determined as $\Psi_1=\Psi-\beta\Psi_0$, where Ψ is the full magnetic flux through the polar cap outer boundary, Ψ_0 is the magnetic flux through the "old" (inner) polar cap, observed prior to the substorm. This inner polar cap is the ionospheric base of the magnetosphere's second tail, existing even in quiet time. The Ψ_0 values are comparable with Ψ, the β coefficient takes into account the changes of the inner polar cap during substorms and storms [Mishin et al., 2004]. In this paper these changes are taken into account only indirectly, without direct determination of the variable coefficient, β. Instead, the ε* values are calculated using the Kan and Lee formula

[1979], modified by the authors. Such an approach does not provide the due regard for the inner tail changes, but allows to take into account the no less strong effect of the polar ionosphere electric field saturation, see Kuzminykh et al., this Seminar.

[6] We applied the *SYM*-H* indices being a minute analog of the D_{*st} index [Iyemory and Rao, 1996], which is important when calculating τ because only these indices contain the information on processes with duration under one hour [e.g., Maltsev, et al., 2003; Liemohn, et al., 2001].

2. Database

[7] In this paper we used the solar wind parameters measured at ACE and WIND (D.J. McComas, ACE Science Center), *AE*-indices the authors obtained from the H-magnetograms of 59 high latitude magnetometers at Φ> 40 °, and the *SYM-H* indices obtained from the WDC-C2 World Data Center, Kyoto [Iyemory et al., 1996] (below these indices are designated by letter S). Calculations of the Poynting flux ε*, Q_i, and Q_{DR} are carried out on the basis of the magnetogram inversion technique [Mishin, 1990] and the array of 115 ground-based magnetometers at Φ> 40°. As the reference level, we adopted the mean values of δX, δY, δZ for the first two hours 20 Nov 2003, when the *AE*-indices did not exceed 50 nT. The solar wind parameters measured by ACE were translated to the dayside magnetopause with the additional delay of $\Delta t^* = (\Delta t - 6)$ (in minutes), where $\Delta t = (x - 10R_E)/V_{sw}$, x is the geocentric distance of ACE along the X axis [Mishin, et al., 2007].

The 20 Nov 2003 magnetospheric superstorm is one of the two strongest disturbances (by intensity) within 1957 - 2003. The D_{*st} index reached - 472 nT, the polar cap potential difference exceeded 200 кV, the polar cap boundary extended up to Φ=60°, the plasma sheet density at the geosynchronous orbit reached 5 cm.$^{-3}$, and its inner edge penetrated up to L~1.5 R_E [Ebihara et al., 2005].

3. Superstorm's Regimes

[8]. The plots in Figure 1 show the boundary conditions during the superstorm under consideration. Vertical dashed lines mark the boundaries of seven disturbance regimes which were timed and described by [Mishin et al., 2007]. The regimes are as follows:

(1) Weak (*AE* <500 nT) isolated substorm, (0300-0417) UT;

(2) Moderate (*AE* up to ~800 nT), rather driven than spontaneous, disturbances (0417-0802) UT;

(3) Transient regime of the P_d (solar wind dynamic pressure) fast amplification in the southern IMF, (0802 - 0824) UT;

(4) Steady regime of high P_d (0824-10300) UT;

(5) Regime of "magnetosphere's zero response" to the IMF turning northward and simultaneous strong (by an order of magnitude) decrease of P_d (1030-1112) UT [Lyons et al., 2005];

(6) Regime of the ε redistribution between the ionosphere and ring current (1112-1210) UT, initiated by sharp increase of the ε input power transported into the magnetosphere;

(7) Regime of driven superstorm with superposition of spontaneous substorms at ε extremes ~10^{13} W, (1210-1400) UT.

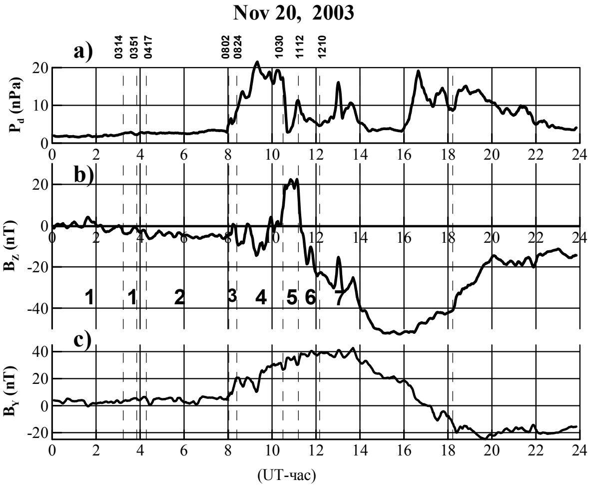

Figure 1. The 20 Nov 2003 superstorm. Top to down: dynamic pressure, P_d *(a)*; IMF components - B_z and B_y (nT) by ACE (*b and c*). Vertical lines mark the boundaries of the superstorm's separate regimes for the interval 03:00-014:00 UT.

4. Basic Equations

[9]. The Dessler-Parker-Skopke equation (DPS) is a DR ring current magnetic field (nT) as the function of its particles' energy, total energy of the dipole geomagnetic field outside Earth, and intensity of the terrestrial dipole geomagnetic field at the equator:

$$DR\ (nT) = B_0 (2\ U_k / 3U_m) \qquad (1)$$

where B_0 is the intensity of the terrestrial dipole geomagnetic field at the equator, U_m is the total energy of the dipole geomagnetic field outside Earth, U_k is the energy of the DR current particles.

To estimate τ, they apply the modified DPS equation [Burton et al., 1975, Akasofu,1981], where the energy U_k is replaced by its derivative $C \cdot dU_k/dt = Q_{DR}$, and the equation is supplemented with a summand, which, along with Q_{DR}, takes into account the DR-current decay time, τ (s). The equation can be written as

$$\tau = \frac{C \cdot S^*}{Q_{DR} - C \cdot \dfrac{dS^*}{dt}} \qquad (2)$$

Here, $C = 4 \cdot 10^{13}$ W·s/nT, S* are SYM*-H indices the DR-current magnetic field, referenced from the quiet day level and fully corrected for the solar wind pressure effect, the Earth induced current contributions, and tail currents Turner et al. [2001].

[10] Q_{DR} - the power consumed by ring current - is found from the expression for storm total power where $\mathbf{Q}_T$ is the power of the tail currents, $\mathbf{Q}_i$ is the power of the Joule heating the ionosphere, $\mathbf{Q}_A$ is the power of the particles precipitating into the ionosphere [e.g., Akasofu, 1981]. Using the empirical relation $Q_{DR} = Q_T$ [Turner et al., 2001], we have

$$Q = 2Q_{DR} + Q_i + Q_A. \qquad (3)$$

Let us designate the total power consumed in the ionosphere

$$Q_i^* = Q_i + Q_A \qquad (4)$$

According to Ostgaard [2002] the Q_i/Q_A relation vary within 2-4. On this ground we accept $Q_i/Q_A = 3$ and

$$Q_i^* = 2Q'_i\,(1+0.33) \qquad (5)$$

where Q'_i is the power of the Joule heating the ionosphere for one hemisphere, determined by the magnetogram inversion technique (MIT-2) [Mishin et al., 1990]. The Q_{DR} parameter is calculated on the basis of the equations (4) ÷ (6):

$$Q_{DR} = 0.5(Q - Q_i^*) \qquad (6)$$

To calculate Q, in the right side of the equations (7), we applied

$$Q = k\varepsilon^* \qquad (7)$$

where k is the coefficient, changing with the superstorm's regimes within $0 < k < 1$ [Mishin et al., 2007].

[11]. The τ_T values are calculated on the basis of the equation (2). Unlike the normal MIT-2, in this paper, when determinating $\varepsilon = \varepsilon^*$, we applied the equation

$$\Phi_{pc} = c(\mu_0/4\pi)\varepsilon^* \cdot V_{SW})^{0.5} \qquad (8),$$

where we accepted

$$c \neq 1 \qquad (9).$$

We note that in the Kan and Lee model [1979] c=1 is postulated. The equation (8) with $c\neq1$ takes into account the strong effect of the ionospheric electric field saturation [e.g., Siscoe et al., 2002]. This circumstance determined the title of this paper.

On the basis of the equations (8), (9) we obtained

$$\varepsilon^* = (4\cdot\pi\cdot\Phi_{pc}^2)/(c^2\,\mu_0\,V_{sw}), \qquad (10),$$

where the c coefficient in (10) is calculated empirically: c=0.38 [Kuzminykh et al., the present collected papers].

5. Results and Discussion

[12] The τ_T plots are presented in Figure 2 where each step in the plot corresponds to one of the regimes above. The mean-square deviations from average ones for each regime are shown. It is evident that the τ_T values distinctly change at the boundaries of almost all the listed above superstorm's 7 regimes, timed independently [Mishin et al., 2007]. At transitions from Regime 1 to Regimes 1, 2, 3, 4, 5, and 7, the τ_T typical values are, respectively, ~ (1.8 - 0.6), 1.1, 0.7, 0.5, 1.5, 0.5 and 0.4 hours, with the mean-square error of ≤20 % from the τ_T mean values in each regime.

[13]. We will cite quantitative estimates of τ_T variations when the regimes change.

For the interval 0200-0314 UT (Regime 1), the τ_T mean values range from 1.8±0.36 up to 0.64±0.064 hour at the transition from the isolated substorm growth phase to the active phases.

The interval (0824-1030) UT is characterized by the peak of the solar wind dynamic pressure, reaching over 20 nPa (Figure 1a). Here, the τ_T mean values decrease from 1.1 to 0.46 hour, over twice as much, compared with previous Regime 2 of moderate disturbance.

The IMF turning northward within the interval 1030-1112 UT (Figure 1.a) was accompanied by a sharp decrease of solar wind pressure, which is noted by increase of the τ_T value up to 1.5 hours, i.e. threefold. The IMF next turning southward caused growth of the ε^* input power into the magnetosphere and decrease of the ring current decay time in the interval 1112-1210 UT to 0.5 hour.

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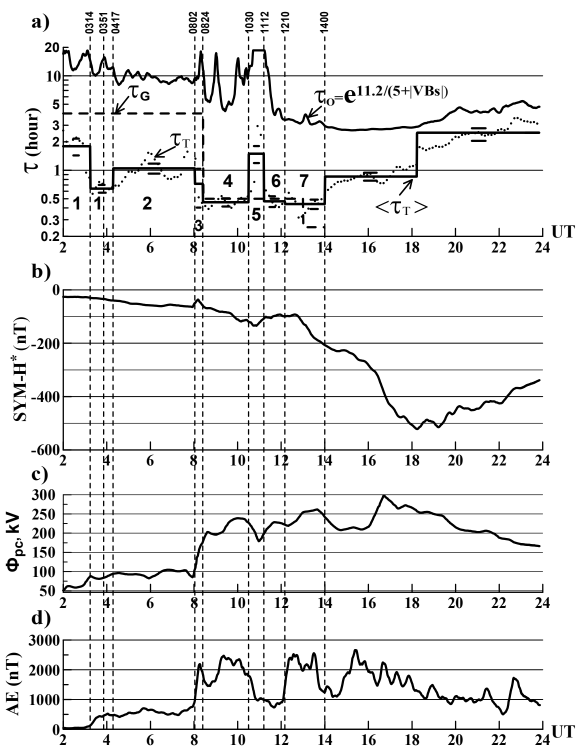

Figure 2. The DR-current decay time: τ_O - after O'Brien and McPherron, τ_G - after Gonzalez et al., τ_T and $<\tau_T>$ - dotted line and solid line, that is averages for each substorm's regime marked 1 to 7 (a); *SYM-H** is index corrected for solar wind dynamic pressure (b), Φ_{PC} - the polar cap potential drop with saturation taken into account [Ebihara, et al., 2005] (c); *AE* auroral activity index (d).

[14] Within the interval 1300-1813 UT, the most intensive growth of the magnetic field of the symmetric DR-current, dS/dt=80 nT/hour, is observed. Here one should have expected decrease of the τ_T value, however, the opposite trend (Figure. 2b) is observed. This fact shows the strong effect of the polar cap ionosphere electric potential saturation which is well seen in the Φ_{pc} plot from [Ebihara, 2005] (Figure 2c). The saturation results in redistribution of the disturbance power between the ionosphere and ring current in favor of the partial (asymmetric) ring current [Mishin et al., 2007].

[15] From comparison of the τ_O and τ_G plots in Figure 2a follows that these two values during the superstorm (τ_O especially) do not correlate with the observed changes of the substorm's regimes. On the other hand, we noted that the τ_T values distinctly change at the boundaries of all the listed above superstorm's 7 regimes. This fact is the principal result of the work carried out. It is also important to note that the τ_T mean values in the main phase (0200-1400 UT) are much

closer to τ_G from the Model [Gonzalez et al. [1989], but in the "recovery" stage they are closer to τ_O [O'Brien et al., 2000].

5. Conclusions

[16] In general, application of the new method for the first time provided the τ scale which takes into account 7 various regimes of magnetospheric disturbance. In the new scale the τ_T values in the storm main phase are manifold or by an order of magnitude lower than the corresponding τ_O values. We noted the causes of some distinctions revealed, including the effect of the ionospheric electric field saturation. We continue the study, using new observational data and the improved technique of determining the Poynting input flux ε.

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