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THE POINTS OF CONTROVERSY IN MAGNETIC STORM STUDY (REVIEW)

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Abstract. In the present review we concentrate on the most important and so far unresolved problems concerning morphology and physics of magnetic storms, namely, 1) which currents are responsible for the *Dst* variation; 2) which geophysical factors mostly control the *Dst* index and what the underlying physics is; 3) why the latitude of the auroral electrojets and energetic particle precipitation decreases during storms; 4) if there is actually a storm-to-substorm relation. We present major experimental result and theoretical view on each of the above problems.

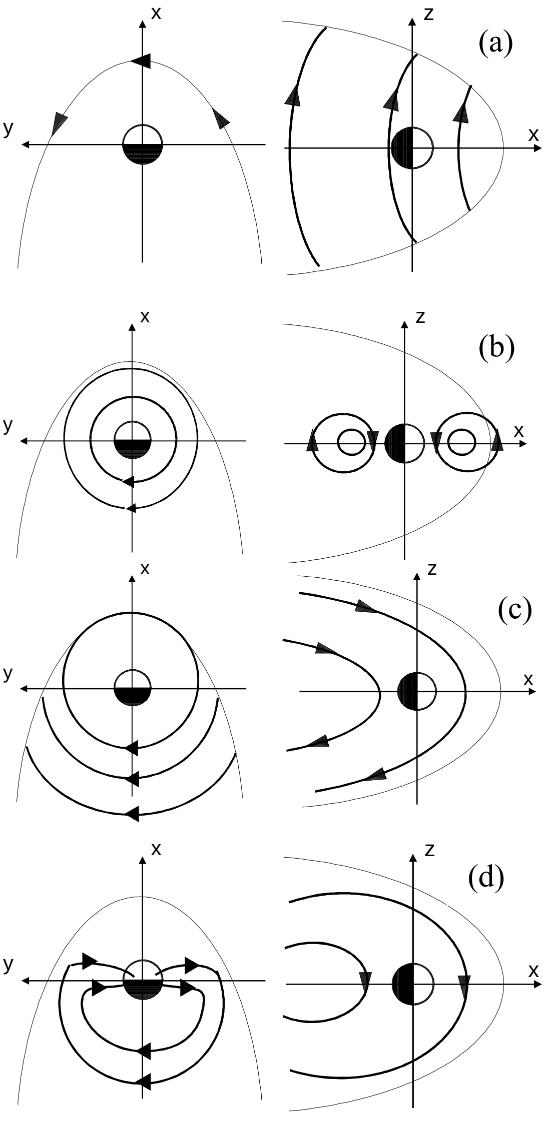

Figure 1. Sketch of (left) the electric currents and (right) the associated magnetic disturbances for the four "elementary" current systems contributing to *Dst* [*Maltsev and Ostapenko*, 2002b]. From top to bottom: magnetopause currents shielding Earth's dipole and ring current, symmetric ring current, cross-tail current along with the closure current on the magnetopause, and partial ring current closed to the Region 2 field-aligned currents.

Introduction

Magnetospheric storm is a phenomenon which typically lasts from one to three days and involves the whole magnetosphere from the ground up to the far tail. On the ground a global depression of the magnetic field is observed which is called a geomagnetic (or magnetic) storm. A measure of the storm intensity is the *Dst* index determined as the disturbed low-latitude *H* component averaged over longitude. It is generally accepted that the storm occurs if the *Dst* becomes lower than –50 nT. Annually according to this criterion 30-40 storm events happen.

The main purpose of the present review is to draw reader's attention to a few acute and highly debatable problems concerning morphology and physics of magnetic storms.

1. Electric currents responsible for the *Dst* variation

Four large-scale magnetospheric currents which can contribute to the *Dst* variation are sketched in Figure 1 (left) [*Maltsev and Ostapenko*, 2002b]. Note that each of the systems is closed. In Figure 1 (right) are sketched the magnetic disturbances produced by each of the "elementary" current systems. Thus, the *Dst* variation can be presented as

$$Dst = k\,[B_z^{mp}(0) + B_z^{rc}(0) + B_z^{ct}(0) + B_z^{prc}(0)] - H_q \quad (1)$$

where in the square brackets is the sum of the magnetic effects of the magnetopause shielding currents, symmetric ring currents, cross-tail currents along with the closure currents on the magnetopause, and partial ring current, respectively, all the effects being referred to Earth's center; $k \approx 1.3$ is the amplifying coefficient due to the currents unduced inside the Earth [*Häkkinen et al.,* 2002]; H_q is the geomagnetic effect of the same currents under quiet conditions.

Now we shall consider the observations that enable to estimate separately the contribution of the each "elementary" current system to *Dst*.

1.1. Contribution to the *Dst* of the shielding currents on the magnetopause

The magnetic field of the shielding current on the magnetopause can be found from the *Mead* [1964] model

$$B_z^{mp}(0) \approx 0.3\,B_s \quad (2)$$

where B_s is the magnetic field at the subsolar point on the magnetopause which can be obtained from the pressure balance condition

$$B_s = \sqrt{2\mu_0 p_{sw}} \quad (3)$$

where μ_0 is the magnetic permeability of vacuum, p_{sw} is the solar wind pressure at the stagnation point, which is nearly equal to the dynamic pressure of the solar wind protons p_{sw}^{dyn}. Having taken B_z in nT, p_{sw}^{dyn} in nPa and by substituting (3) into (2) we get

$$B_z^{mp}(0) \approx 17\sqrt{p_{sw}^{dyn}} \tag{4}$$

The solar wind dynamic pressure is equal to ~2 nPa under quiet conditions and increases up to ~4 nPa during typical storms. According to formula (4) this enhancement produces $B_z^{mp}(0) \approx 10$ nT, i.e. provides a slight compression of the field.

1.2. Contribution of the symmetric ring current

The ring current effect is estimated from the well-known Dessler-Parker-Sckopke (DPS) formula

$$B_z^{rc}(0) = -\frac{\mu_0}{4\pi}\frac{2E_{RC}}{M_E} \tag{5}$$

in which E_{RC} is the total energy of the particles trapped in the dipolar magnetic field, M_E being the Earth magnetic moment.

The first statistical study of this relation was performed by *Greenspan and Hamilton* [2000]. During 80 storm events the AMPTE CCE satellite registered the energy content E_{RC} at distances from $L = 2$ to $L = 7$. In Figure 2 the resulting dependence of *Dst* on E_{RC} is shown. One can see the lack of any correlation between the dayside energy content and *Dst*, while at night there is a good correlation. We should keep in mind that it is only the symmetric ring current that flows at the dayside, whereas at night there are also cross-tail and partial ring currents. The right panel of Figure 2 suggests that the symmetric ring current is practically not related to *Dst* and can hardly be considered as the principal cause of geomagnetic depression.

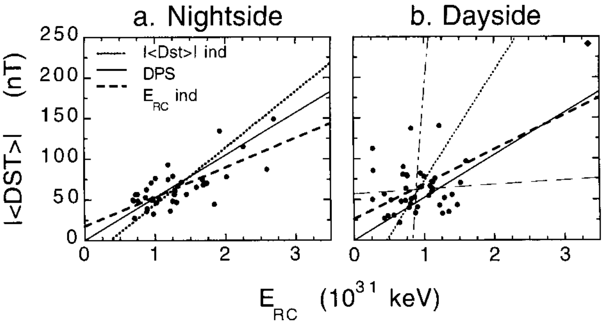

Figure 2. *Dst* index versus the energy content (circles) as indicated by the AMPTE observations [*Greenspan and Hamilton,* 2000] (left) at the nightside, (right) at the dayside. The solid lines present the dependence expected from the Dessler-Parker-Sckopke formula.

The second (and so far the latest statistical study) by *Turner et al.* [2001] gives somewhat different results. The authors restored the total energy content E_{rc} in four MLT sectors from particle observations by the *Polar* satellite and found that under moderate disturbances (*Dst** > -50 nT) the symmetric ring current provides about 75% contribution to *Dst*. With the storm intensifying its contribution drops down to about 40% (under *Dst* = -100 nT). It should be mentioned that the *Polar* satellite which orbit lay in the meridian plane could registered only a small portion of the trapped particles. To restore the total number from the portion detected, *Turner et al.* [2001] had to use some speculations.

The research performed by *De Michelis et al.* [1999], though indirectly supports the viewpoint that the contribution of the symmetric ring current to the *Dst* index is small. Based on the AMPTE CCE observations, the authors restore radial pressure profiles in the equatorial plane for four MLT sectors under low (*AE* < 100 nT) and high (100 < *AE* < 600 nT) levels of geomagnetic disturbance The profiles appear to be nearly insensitive to the AE values. Since the *AE* and *Dst* indices are known to indicate a close statistical relationship, it can be inferred that the energy content is independent of the *Dst* either.

1.3. Contribution of the cross-tail current system

We define the cross-tail current as the one flowing near the equatorial plane and being closed via the magnetopause. This way of closing makes it different from the ring current, which is closed within the magnetosphere. The cross-tail current system includes the cross-tail current proper and closure currents on the magnetopause. So far the contribution of the cross-tail current system to the *Dst* has been described in three different manners. Let us consider each of them in detail.

1.3.1. Cross-tail current contribution as follows from the high-latitude magnetic flux

The magnetic effect of the magnetotail current system including the cross-tail current, closure currents on the magnetopause, and partial ring current can be estimated from the *Maltsev* [1991] formula

$$B_z^{ct}(0) = -\frac{F}{3S} \tag{6}$$

where S is the cross-section of the inner magnetosphere delineated by the contour $B = B_s$, B_s being the magnetic field at the subsolar point, F is the magnetic flux beyond this contour.

We consider the boundary between the inner and outer magnetospheric regions to be associated with the equatorward edge of the auroral oval. This supposition is based on the results of *Feldstein and Starkov* [1970], *Sergeev et al.* [1983], *Kirkwood and Eliasson* [1990], which relate the equatorward edge of the oval to the poleward boundary of the energetic (>40 keV) electron trapping region. Thus for the high latitude magnetic flux we can write

$$F = 2\pi R_E^2 B_e \sin^2\theta_a\ , \tag{7}$$

where B_e = 31000 nT is the dipole magnetic field at Earth's equator, θ_a is the colatitude of the equatorward edge of the auroral oval averaged over longitude. For storm conditions the area of equatorial cross-section S is equal to [*Maltsev et al.*, 1996]

$$S = \frac{9}{4}\frac{\pi R_E^2}{\sin^4\theta_a} \tag{8}$$

Substitution of (7) and (8) into (6) yields

$$B_z^{ct}(0) = -\frac{8}{27}B_e\sin^6\theta_a \tag{9}$$

During storms the auroral oval is displaced to lower latitudes. *Starkov* [1993] proposed the following empirical relation between the latitude Λ of the oval equatorward edge and *Dst* index

$$\Lambda = 74.9° - 8.6\log_{10}|Dst| \tag{10}$$

The auroral oval equatorward boundary under disturbed conditions can be approximated by a circle centered at latitude of 85° at midnight [*Starkov and Feldstein*, 1967]. Then for the nighttime MLT sector one can get

$$\Lambda = 85° - \theta_a \tag{11}$$

Thus having adopted *Dst* = –400 nT, we get from (10): $\Lambda = 52.5°$ and from (11) $\theta_a = 32.5°$. After substituting this value into (9), we have $B_z^{ct}(0) \approx -220$ nT. Multiplying this quantity by the coefficient 1.3 due to the induction currents inside the Earth, we get the disturbance equal to –290 nT, which provides more than 70% contribution to the *Dst* index.

1.3.2. Cross-tail current contribution estimated with the use of the Bio-Savart-Laplace law

This method required knowledge of the magnetospheric currents. It is convenient to relate the effect of the cross-tail current system to observations at geosynchronous distance, for during storms the stable trapping region contracts, so that a geosynchronous satellite at midnight appears in the tail-like magnetic field. Therefore, the magnetic disturbance produced in Earth's center by the cross-tail current system is

$$B_z^{ct}(0) = \kappa\, B_x(x = -6.6\ R_E,\ y = 0,\ z = 5\ R_E)$$

where the coefficient κ mostly depends on the distance to the near edge of the cross-tail current. In the model of *Tsyganenko and Sibeck* [1994] this coefficient turns out to be ~1.5. Somewhat smaller value ($\kappa \sim 0.7$) follows from the paraboloid model of *Alexeev et al.* [1996]. Under quiet conditions the magnetic field in the tail lobes is typically about 20 nT. Under disturbed conditions its magnitude is several times greater [*Kaufmann*, 1987]. Statistical studies of the geosynchronous B_x component behavior versus *Dst* have not been performed yet. A preliminary examination performed by *Bolshov* [1995] indicated $B_x \approx Dst$. Having taking $\kappa = 0.7$, we get 70% contribution to *Dst* with the effect of the induction currents inside the Earth being included. For the storm of March 24, 1969 ($Dst_{\min}$ = -210 nT) *Alexeev et al.* [1996] found $B_z^{ct}(0) \approx -120$ nT, which along with induction currents provides 70% contribution to *Dst*.

The cross-tail current model used by *Turner et al.* [2000] seems to be not quite complete. The authors only include into treatment a part of the cross-tail current flowing at distances $x < -6\ R_E$. Neither the cross-tail current portion adjacent to the magnetospheric flanks at $x > -6\ R_E$ (Figure 1c, left), nor the closure currents on the magnetopause were considered. Under these restrictions the authors evaluate the cross-tail current contribution to *Dst* as 25%, which is obviously underestimated. As is shown by *Maltsev and Ostapenko* [2002a] the near-flank portion of the dayside current flowing beyond the stable trapping region, i.e. being closed on the magnetopause, enhances the magnetic effect considered by 60%. Besides, according to the model of *Tsyganenko and Sibeck* [1994] the contribution of the magnetopause closure currents enlarges the magnetic effect being discussed by factor ~1.5.

Antonova [2001] asserted that the electric current responsible for the strong stretching of the magnetic field at the geosynchronous orbit can not close to the magnetopause because in the case examined by *Alexeev et al.* [1996] the plasma pressure at geosynchronous distance exceeded the solar wind dynamic pressure, and according to the magnetostatic equilibrium condition $[\mathbf{j}\times\mathbf{B}] = \nabla p$, the electric current must flow along the contours of constant pressure *p*. It is possible, however, that during the storm explored by *Alexeev et al.* [1996] the growth not of the cross-tail current but of the partial ring current occurred, the enhancement of the latter being also associated with the transferring of the magnetic flux from the dayside to the magnetotail.

1.3.3. Cross-tail current contribution inferred from the magnetic field distribution in the plane *x* = 0

As is seen from Figure 1b, right, the symmetric ring current does not produce a normal component of the magnetic perturbation in the plane $x = 0$, which separates the daytime and nighttime magnetospheric regions. Thus it is convenient to use magnetic observations near this plane to evaluate the geomagnetic effect of all the other magnetospheric currents. With this purpose *Maltsev and Ostapenko* [2002a] processed the database by *Fairfield et al.* [1994] and estimated the distribution of the differential response of the B_x component in the plane $x = 0$ to the *Dst* variation as δDst = -81 nT. This distribution was used as the Neumann type boundary condition for the Laplace equation which describes the scalar magnetic potential in the daytime magnetosphere. The solution of this equation yields the following differential response of the magnetic field on the ground: $\delta B_z^{mp}(0) + \delta B_z^{ct}(0) + \delta B_z^{prc}(0) \approx -50$ nT. Having excluded the effect of the magnetopause shielding currents $\delta B_z^{mp}(0) \approx 5$ nT and taken into account the induction currents inside the Earth, we get more than 80% contribution of the cross-tail and partial ring current to *Dst*. Further it will be demonstrated that the contribution of the partial ring current amounts to ~15%.

1.4. Partial ring current contribution

Magnetic effect of the partial ring current can be estimated from the Bio-Savart-Laplace law

$$B_z^{prc}(0) = -\frac{\mu_0}{4\pi}\frac{1}{r}\int_0^{2\pi} I_{prc}(\varphi)\, d\varphi \tag{12}$$

where φ is the longitude. According to (12), the partial ring current of 1 MA magnitude flowing in a 12 hour MLT sector at distance of 6 R_E produces $B_z^{prc}(0) \approx -8$ nT. The partial ring current is closed by the Region 2 field-aligned currents (FAC). The total Region 2 FAC in each hemisphere is equal to 1 MA for $|AL| < 100$ nT and 1.9 MA for $|AL| > 100$ nT [*Iijima and Potemra*, 1976]. The corresponding values of the partial ring current are 2 and 3.8 MA, respectively, with the associated magnetic perturbation $B_z^{prc}(0)$ equal to –16 and –30 nT. *Maltsev and Ostapenko* [2003] obtained the FAC distribution at ionosphere altitudes under five levels of *Dst*. The results indicate the following empirical relationship for the maximum value of the partial ring current

$$I_{prc\,max}\ (\mathrm{MA}) = 1.28 - 0.013\ Dst \tag{13}$$

Having substituted (13) into (12) and (1), we obtain ~15% contribution of the partial ring current to *Dst*.

Liemohn et al. [2001] through numerical simulation obtained the contribution of the partial ring current to *Dst* at the main phase of the storm as large as 80%. However, these authors neglected the effect of the polarization electric field originating due to charge separation in the course of the sunward convection. This field is known to decrease significantly the magnitude of the partial ring current.

2. Geophysical factors controlling the *Dst* index

2.1. Morphology

In examining storm time behavior of *Dst* index, it is typically presented as a sum of the rapidly and slowly varying components

$$Dst = DCF + Dst^* \qquad (14)$$

where *DCF* is the rapidly varying (on a time scale of a few minutes) component, which is controlled by the solar wind dynamic pressure; *Dst** is the component varying on the time scale of several hours.

Both the shielding current on the magnetopause and cross-tail current system contribute to *DCF* [*Ostapenko and Maltsev*, 1998]. It is typically accepted that

$$DCF = a\sqrt{p_{sw}^{dyn}} \qquad (15)$$

where *a* is the coefficient that will be discussed further, p_{sw}^{dyn} is the dynamic pressure of the solar wind protons. In the study of *O'Brien and Mcpherron* [2000] it is shown that the value of *a* averaged over 30 years amounts to 7.26 nT/(nPa)$^{1/2}$. Based on the same database, *Maltsev and Rezhenov* [2002] investigated the value of *a* versus B_z IMF and *Dst* and obtained that under quiet and moderately disturbed conditions $a \approx 8$ nT/(nPa)$^{1/2}$. Under $Dst < -100$ nT and B_zIMF < -5 nT the value of *a* decreases by factor 2. Note, that formula (4) predicts $a \approx 22$ nT/(nPa)$^{1/2}$. One should keep in mind, that $B_z^{mp}(0)$ must be multiplied by factor 1.3 due to the induction currents inside the Earth. The observed decrease in the value of *a* is probably associated with the damping effect of the cross-tail current.

The behavior of the slowly varying component of *Dst* is commonly described by the following differential equation

$$\frac{dDst^*}{dt} = Q - \frac{Dst^*}{\tau} \qquad (16)$$

where τ is the relaxation time, *Q* is the coupling function of *Dst* with the solar wind. The first treatment of the coupling function *Q* dates back to 1970th. *Burton et al.* [1975] found that *Q* is linearly proportional to the duskward component of the solar wind electric field. Then, a great number of researches were performed, in which relation of the coupling function to other solar wind parameters was clarified. Table 1 summarizes the principal experimentally observed features of *Q* and τ for the main phase (τ_{mp}) and recovery phase (τ_{rp}) of the storm. In Table 1 *Q* is expressed in nT/hr, τ in hrs, B_zIMF, B_sIMF as well as the IMF variability σ are in nT, the electric field component $E_y = -VB_z$ is in mV/m, the solar wind velocity *V* is in km/s, the quantity $E_y^r = -V B_s$ is the duskward electric field component, B_s is the southward IMF component in the GSM coordinates, such that $B_s = B_z$ under $B_z < 0$ and $B_s = 0$ under $B_z > 0$, $\varepsilon = VB^2\sin^4(\theta/2)l_o^2$ is the Akasofu parameter, *B* is the IMF modulus, $\theta = \arctan(B_y/B_z)$, $l_o \approx 7R_E$ is the effective transverse size of the magnetosphere.

From Table 1 we can see that there is some deal of controversy when determining the values of *Q* and τ. The discrepancy is most probably results from a strong correlation between various solar wind parameters. In [*Maltsev and Rezhenov*, 2003] an attempt was made to exclude this misleading effect. With this purpose, the authors treated the dependence of *dDst*/*dt* on a given solar wind parameter with all the others being fixed or varying in a narrow range. The authors have not detected any noticeable relation to the solar wind density or horizontal IMF component. The dependence on the Akasofu parameter under the electric field $E_y^r = -VB_s$ being fixed appeared to be much weaker than that on the electric field E_y^r under constant ε. This suggests that the Akasofu parameter ε hardly has any advantages over E_y^r.

Most of the results presented in Table 1 suggest rather linear coupling of *Dst* with the solar wind parameters and strongly non-linear decay dependent on both *Dst* and *Q*. However the technique for calculating *Q* and τ does not yield a unique solution. In particular, the results of Maltsev and Rezhenov [2003] can be presented as $Q = 1.05 - E_y^r\,(4.00 + Dst^*/47.2) - V/243$ and $\tau = 15.4$ hr. Thus we have the non-linear coupling and linear decay. The same transformation could be done with other *Q* and τ shown in Table 1.

2.2. Theoretical views on the *Dst* relation to the solar wind parameters

Theoretical framework of the coupling function *Q* has been developed by *Maltsev* [1991], *Arykov and Maltsev* [1996], *Maltsev* [2002] with concentrating on the magnetotail current effect in *Dst*, including the cross-tail current, closure currents on the magnetopause, and partial ring current. Having differentiating (7) with respect to t and keeping in mind that, according to (7) and (8), *S* is proportional to F^{-2}, we have

$$\frac{dB_z^{ct}(0)}{dt} = -\frac{1}{S}\frac{dF}{dt} \qquad (17)$$

The high latitude magnetic flux satisfies the equation

$$\frac{dF}{dt} = U - \frac{F - F_0}{\tau_F} \qquad (18)$$

where *U* is the convection-associated potential drop between the dawn and dusk boundaries of the inner magnetosphere, F_0 is the undisturbed quantity of the flux, τ_F is the relaxation time. With the induction currents inside the Earth being included, the geomagnetic disturbance is

$$H^{ct} = k\,B_z^{ct}(0) \qquad (19)$$

where $k \sim 1.3$. The potential *U* is equal to

Table 1. Coupling function Q relating the Dst index to solar wind parameters and relaxation times of the storm-associated currents τ_{mp} and τ_{rp} for the main and recovery phases of storm, respectively, as summarized by different studies

No	Reference	Q	τ_{mp}	τ_{rp}
1	*Murayama* (1982)	$Q \sim B_s V (mnV^2)^{1/3}$	$\tau = 12$ hr	
2	*Pudovkin et al*. [1988]	$Q = -3.5 + 4.3\, V(0.56 - B_z)\times 10^{-3}$ for $V(0.56 - B_z) \geq 1.5\times 10^3$ $Q = 3$ nT/hr for $0 \leq V(0.56 - B_z) \leq 1.5\times 10^3$ $Q = 0$ for $0 \leq V(0.56 - B_z) < 0$	$\tau = 3.0 + 9.8\, e^{-Q/4.5}$	$\tau = 6.6 + 0.07 \lvert Dst^* \rvert$
3	*Grafe* (1988)	$Q = -4.32\,(E_y + 0.9)$	$5 \leq \tau \leq 40$ hr ($-50 < Q < -5$ nT/hr)	$100 > \tau > 12$ hr ($-90 > Dst^* > -280$ nT)
4	*Feldstein* [1992]	$Q = 8.2\times 10^{-3} V(B_z - 0.67\sigma) -$ $- 14.1\times 10^{-3}\,(V - 300) + 9.4$	Weak and moderate storms ($Dst^* > -160$ nT):	
		for $V(B_z - 0.67\sigma) < -1146$	$\tau = 1.6 + 13\, e^{0.08Q}$	$\tau = 5.4 + 10\, e^{0.025Dsto}$
		$Q = -14.1\times 10^{-3}\,(V - 300)$	Strong storms ($Dst^* < -160$ нТл):	
		for $V(B_z - 0.67\sigma) > -1146$	$\tau = 2.4 + 13\, e^{0.07Q}$	$\tau = 10 + 1.84 e^{0.07Dsto}$
5	*Gonzalez et al*. [1989, 1994]	$Q \propto -\varepsilon$	$\tau = 4$ hr for $Dst \geq -50$ nT $\tau = 0.5$ hr for $-50 > Dst \geq -120$ nT $\tau = 0.25$ hr for $Dst < -120$ nT	
6	*Valdivia et al*. [1996]	$Q = -0.26\, E_y^r$	$\tau = 12.5/(1 - 0.0012\, Dst^*)$	
7	*O'Brien and McPherron* [2000]	$Q = -4.4\,(E_y - 0.5)$ for $E_y > 0.49$ mV/m $Q = 0$ for $E_y < 0.49$ mV/m	$\tau = 2.40 \exp[9.74/(4.69 + E_y^r)]$	
8	*Maltsev and Rezhenov* [2003]	$Q = 1.05 - 4.00\, E_{yr} - V/243$	$\tau = 15.4/(1 + 0.326\, E_y^r)$.	

$$U = \chi U_{PC}, \tag{20}$$

where U_{PC} is the convection potential drop between the dawn and dusk flanks of the whole magnetosphere which are mapped onto the polar cap boundary; χ is a certain coefficient ($\chi < 1$). After substituting (18)-(20) into (17), we have

$$\frac{dH^{ct}}{dt} = Q^{ct} - 3\frac{H^{ct}}{\tau_F} - k\frac{F_0}{S\,\tau_F} \tag{21}$$

where

$$Q^{ct} = -k\chi\frac{U_{PC}}{S} \tag{22}$$

is the coupling function relating the magnetotail current to the solar wind conditions. *Doyle and Burke* [1983] obtained the following empirical formula

$$U_{pc}\,(\text{kV}) = 55.3 + 14\, E_y\,(\text{mV/m}) \tag{23}$$

Having substituted (23) into (22), with $k = 1.3$, $\chi = 0.5$, $S = 7.5\times 10^{15}$ m^2 (this corresponds to the circle with the radius of 7.7 R_E), we can get

$$Q^{ct}\,(\text{nT/hr}) = -4.4\, E_y(\text{mV/m}) - 16.$$

From comparing with Table 1, one can see that the calculated coupling function is close to the observed one (cf. e.g. [*O'Brien and McPherron*, 2000]). Thus we can conclude that the relation of geomagnetic depression to the solar wind parameters can be interpreted entirely in terms of the magnetotail current system.

On the other hand, any theoretical framework for the coupling function which would relate the symmetric ring current to the solar wind parameters is still absent.

3. Physical mechanism responsible for the storm-time decrease of the auroral electrojet and energetic particle precipitation latitude

3.1. Observations

The latitude of the auroral electrojets is known to decrease significantly during storms. According to *Khorosheva* [1986] (Figure 3, left), with Dst varying from 0 to –400 nT, this latitude decreases from 67 to 52° (L changes from 7 to 2.7). *Khorosheva* [1986] emphasized that the AE index fails to indicate the electrojet intensity during storms, as for $Dst < -50$ nT the electrojets get beyond the 12 standard AE stations (11 of which are located at latitudes higher than 65°). A similar conclusion was made by *Feldstein et al.* [1994, 1997]. Figure 3 (right) shows the corrected geomagnetic latitude Φ' of the westward electrojet center, with Φ' decreasing from 59-60° under $Dst = -100$ nT to 54-55° under $Dst = -300$ nT. The solid line is the LST approximation of Φ' under Dst ranging from 0 to –250 nT: $\Phi' = 65.2 + 0.035\, Dst$. *Feldstein et al.* [1994] by using subauroral station magnetograms built the corrected AE index, which during storms appeared to be twice as large as the standard one.

It is known that the latitude of the particle precipitation regions, in particular of the discrete auroral oval, also decreases in the course of a storm. The equatorward edge of the auroral oval can be approximated by a circle centered at midnight at the latitude of 87° under quiet conditions and 85° under moderately and strongly disturbed conditions [*Starkov and Feldstein*, 1967]. The radius of this circle displays a very good correlation with *Dst* [e.g. *Meng*, 1984; *Starkov*, 1993] shown in Figure 4.

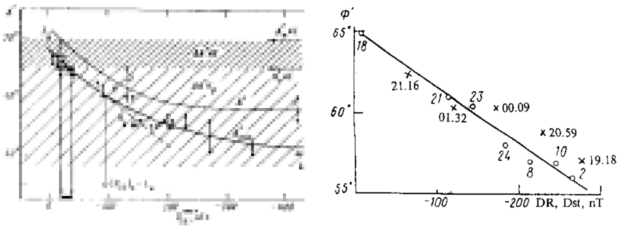

Figure 3. Auroral electrojet location versus *Dst* accordig to (left *Khorosheva* [1986].and (right) [*Feldstein et al.* , 1997].

The discrete auroras are known to be embedded into a wider region of diffuse luminosity. The equatorward edge of this region, which latitude is ~10° lower compared to the discrete oval, also drifts toward the equator with the growth of geomagnetic activity [*Starkov*, 1993]. In particular, SAR arcs connected with the diffuse precipitation are sometimes observed at $L = 1.7$ during strong storms ($Dst = -430$ nT) [*Khorosheva*, 1987].

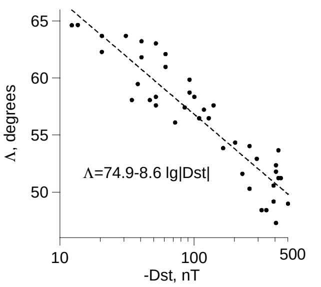

Figure 4. Latitude of the auroral oval equatorward edge in the dusk-midnight sector versus *Dst* [*Starkov*, 1993]. The points indicate observations, the dashed line is approximation.

The dayside polar cusps also shift from the latitude of ~76° under average conditions [*Newell and Meng*, 1989] to ~60° and lower under storms, as occurred during the storm of December 19, 1980 ($Dst = -250$ nT) [*Bering et al.*, 1991].

3.2. Theoretical framework for the storm time decrease of the auroral oval latitude

The equatorward edge of the auroral oval at the nightside within the accuracy of ~0.5° is coincident with the outer boundary of the trapped energetic electrons ($E > 40$ keV) [*Feldstein and Starkov*, 1970; *Sergeev et al.*, 1983; *Kirkwood and Eliasson*, 1990]. This means that the electron trapping region is confined within the inner magnetosphere, while the auroral oval is associated with more distant magnetospheric domains. Thus, we should explain why the boundary between the inner and outer magnetospheric regions is moving earthward during storms. Such a reconfiguration of the magnetosphere can be only caused by the large-scale magnetospheric currents, which redistribute the magnetic flux, enhancing it in the outer magnetosphere and decreasing in the inner region.

The first attempt to interpret such a magnetic flux redistribution [*Siscoe*, 1979a] indicated that this could be achieved only if the ring current flew beyond the stable trapping region. In other words, the cross-tail current should be considered as an ultimate cause of this effect. In [*Siscoe*, 1979b] the contribution of the ring current flowing in the stable trapping region to the observed storm time enhancement of the magnetic flux in the polar cap was estimated as 25% only. *Schulz* [1997] found that every 100 nT of the magnetic disturbance in the Earth's center (or 130 nT with the induction currents inside the Earth included) associated with the ring current should replace the auroral oval toward the equator by 5.5°. From Figure 4 it is seen that in reality this displacement is three times larger.

The reason why the ring current can only slightly affect the magnetic flux redistribution between the inner and outer magnetospheric regions is that the area of the magnetic depression region related to the ring current is rather small. It is 3-4 times smaller than that associated with the cross-tail current. *Maltsev et al.* [1996] calculated the expected latitude of the auroral oval equatorward edge for several ratios of *DR* (symmetric ring current effect) to *Dst*. Good agreement with Figure 4 was obtained for *DR*/*Dst* smaller than 50%.

A major role of the cross-tail current in the storm time decrease of the auroral oval latitude is also pointed out by *Alexeev et al.* [1992, 1996, 2001].

4. Storm-to-substorm relation

4.1. Observations

The coupling function Q in equation (16) is sometimes referred to as an injection function, since for a long time the view was widely spread that the storm time depression is enhanced due to substorms. Substorms can develop in the absence of storms, but nearly all storms at the main phase are accompanied by intense substorms.

This hypothesis was first questioned by the work of *Burton et al.* [1975]. The authors demonstrated that the *Dst* index reproduces in detail variations of the solar wind parameters, first of all, those of the B_zIMF, the response time being much smaller than the typical time of substorm development [*McPherron*, 1997]. However, understanding of the storm-to-substorm relation was complicated by the strong correlation of substorms with the southward IMF. In this respect, very indicative are periods of the steady magnetospheric convection, which are characterized by the absence of substorms under persistently southward B_zIMF. In spite of the lack of substorms, magnetic storms are known to develop during such periods. Thus in the event of the steady magnetospheric convection of November 24, 1981 there were no substorms during 10 hours. Nonetheless a storm with $Dst \approx -70$ nT was persisting during this period [*Malkov and Sergeev*, 1991; *Yahnin et al.*, 1994; *Sergeev et al.*, 1996]. Another event was reported by *Zolotukhina et al.* [1999] when during the storm of October 18-19, 1995 (*Dst* varied from 0 to –120 nT for three hours) there were no substorms as suggested by the lack of the Pi2 pulsations, which typically indicate the beginning of substorm expansion.

Perhaps, the final argument against the substorm origin of storms was presented by *Iyemori and Rao* [1996]. Using the superimposed epoch analysis of more than 100 substorms, the authors built average *SYM H* index which is a one-minute resolution analogue of *Dst*, having taken the substorm onset time as zero. The result is shown in Figure 5 separately for 89 substorms during the storm main phase and 97 substorms during the recovery phase. It is seen from Figure 5 that not only there is no storm enhancement at the moment of substorm onset but a slight weakening is observed instead.

At present most of the researches (nearly all the participants of the 6th International Conference on Substorm in Seattle, 2002) share a viewpoint that substorms are not the cause of storms. A few supporters of the opposite viewpoint either question the *Dst* index as a whole [*Friedrich et al.*, 2000], or invoke to the strong enhancement of O^+ ions in the ring current after substorms [*Daglis et al.*, 2000], or propose to modify *Dst*, e.g. by including the field-aligned current effect [*Sun and Akasofu*, 2000].

4.2. Theoretical framework for storm weakening by substorms

Siscoe and Petchek [1997] use the virial theorem for the magnetic disturbance in the Earth's center

$$\frac{B_z^{ext}(0)}{B_e} = -\frac{2E_{RC} + M - \oint p_t \mathbf{r} \cdot \mathbf{n}\, d\sigma}{3M_D} \tag{25}$$

where B_e is the dipole magnetic field at the Earth's equator, E_{RC} is the energy of the trapped particles, M is the magnetic energy of the electric currents, M_D is the dipole magnetic field energy outside the Earth. The quantities being integrated are referred to the magnetopause: p_t is the external pressure, r is the geocentric distance, $d\sigma$ is the surface element, $\mathbf{n}$ is the unit vector normal to the magnetopause. It is well-known that at the substorm growth phase the magnetic energy in the magnetosphere increases. With the beginning of the expansion phase the magnetic energy drops. According to (28), even if the expansion phase is associated with the particle injections into the ring current and corresponding growth of E_{RC}, the magnetic energy decrease can be strong enough for the sum 2 $E_{RC} + M$ to diminish and the geomagnetic depression to weaken.

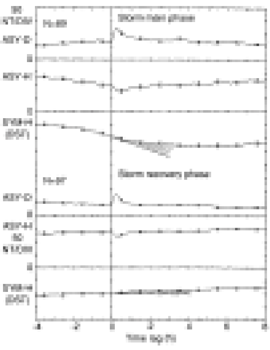

Figure 5. Average behavior of one-minute *Dst* (*SYM H*) and *ASY* indices during substorms [*Iyemori and Rao*, 1996].

Maltsev [2002] points out that there is some inconvenience in using (25), as all the three terms in the RHS of this formula tend to infinity under strong stretching of the magnetotail. It is more convenient to use the following expression [*Maltsev et al.*, 1996]

$$B_z^{ext}(0) = \frac{2}{3}\sqrt{2\mu_0 p_{sw}} + B_z^{rc}(0) - \frac{F}{3S} \tag{26}$$

Formula (26) contains only finite quantities, which can be easily found from observations. Weakening of the storm time depression associated with the substorm onset can be due to the high-latitude magnetic flux F decrease, which is observed in experiment and related to the magnetic field dipolarization during the substorm expansion.

Summary

In conclusion we list the most debatable problems concerning magnetic storm physics.

1) The views of different authors on the ring current effect in the storm time depression are controversial, with the estimates of the symmetric ring current contribution to *Dst* ranging from 0 to 40%.

2) Even greater discrepancy concerns the contributions of the cross-tail and partial ring currents to *Dst*, the corresponding estimates varying from 15-25 to 80%.

3) Most of the researches still use the Akasofu parameter ε in studying the geomagnetic activity versus the solar wind conditions, though the solar wind duskward electric field seems to be more preferable.

4) There is no framework (except for the one developed in section 2) within which the enhancement of the storm time geomagnetic depression could be related to the solar wind electric field.

5) Most of the authors just state but do not interpret the storm time decrease of the auroral oval latitude.

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