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DST-INDEX MODELS: PHYSICAL AND MATHEMATICAL ASPECTS OF MODELING

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Abstract. The procedure of *Dst* modeling proposed in [*Burton et al., J. Geophys. Res.*, 80, 4204, 1975] is widely employed now. It is based on the equations $Dst = DR + DCF$ and $d(DR)/dt = F(E) – DR/\tau$, where the magnetic field generated by currents on the magnetopause is calculated from the solar wind velocity and density: $DCF \sim (NV^2)^{1/2}$, $F(E)$ is rate of ring current injection as a function of a delayed and filtered solar wind electric field, and τ is the characteristic time of ring current decay. Different scientific groups try to increase the accuracy of this method by constructing more and more complicated functions for reproducing the temporal dynamics of the physical processes described by $F(E)$ and τ. As it is known, the *Dst*-index is a measure of the amplitude of geomagnetic disturbance. We aim to find out how this method of *Dst* modeling evaluates physical process of geomagnetic disturbance generation and whether this approach is not mathematical operation only. The variation *Dst(t)* has been modeled for several magnetic storms basing on different *Dst*-index models. It has been demonstrated that in calculating $F(E)$ and τ, the accuracy of the advanced models is the same as that of the models that date back to 1980s. We also argue that physical mechanism responsible for storm-time magnetic disturbances can not be described by above mentioned relations. In our opinion, the advantage of the up-to-date *Dst* models, derived from satellites measurements of space parameters, is an ability to predict mathematically *Dst*-index with the accuracy that is good enough for the applied problems when preliminary information on a possible peak of the cosmic weather activity is needed.

1. Introduction

The *Dst* index plays a unique role as indicator of geomagnetic storm activity: it is a well-defined, readily available empirical quantity that has, by virtue of the Dessler-Parker-Sckopke theorem a physical meaning. Methods for predicting *Dst* time series from measurements of solar wind and other parameters are important for testing theories of geomagnetic storm dynamics as well as for applications to space weather studies. The prediction equation introduced by Button et al., [1975] and their equation with another parameters [*Feldstein, 1992*; *O'Brien and McPherron*, 2000, 2002; *McPherron and O'Brien*, 2001] has proved to be remarkably effective, despite its simplicity. Assuming, on the basis of the Dessler-Parker-Sckopke theorem, that *Dst* represents the total kinetic energy in the ring current plasma, Burton et al. equate the rate of change of *Dst* to an energy source (injection) term minus a loss term (approximated by the use of an effective loss rate); from a fit to observations, they determine the source term as proportional to VB_s for $B_s > 0$ and zero for $B_s < 0$, where V is the solar wind flow speed and B_s ("southward") is the component of the interplanetary magnetic field parallel to the Earth's dipole moment. As conventionally interpreted, their equation determines the evolution of *Dst* entirely from conservation of energy: energy supply and loss rates are taken into account, but the processes by which energy is transferred to ring current plasma are not considered. We try to determine how this method of *Dst* modeling evaluates physical process of geomagnetic disturbance generation and whether this modeling is not mathematical operation only. We modeled *Dst(t)* during some magnetic storms and find that accuracy of the most modern models of *Dst* is the same as accuracy of models [*Feldstein*, 1992] of twenty years' prescription. We also discuss that physical mechanism of current systems generating magnetic disturbances during magnetic storms are not described by the above relations.

2. Physical and mathematical aspects of modeling *Dst = DCF + DR*

Physical aspects of modeling *Dst* in form $Dst = DCF + DR$ consist in the following ideas [*Feldstein*, 1992]. The occurrence of electric current on the magnetosphere surface (*DCF*) and in the region of the outer radiation belt (*DR*) is a consequence of the interaction of solar wind with the frozen-in magnetic field with the geomagnetic field. The *DCF* current are generated when the solar wind compresses the magnetosphere and when the solar wind proton and electron move in opposite directions on the magnetopause. The current system arising on the magnetopause enhances the geomagnetic field intensity inside the magnetosphere. The *DR* currents are due to a rapid increase in the number density of energetic ions in the inner magnetosphere which form an ion belt and are in complicated oscillatory and rotational motions in the Earth's magnetic field. The resultant motions of charged particles are equivalent to $a \sim 10^6$ A intensity electric current shaped as a ring surrounding the Earth in which a fraction of the current in the near-Earth part flows eastwards, while its major fraction is westwards. The total effect of the ring current observed on the Earth's surface is that the horizontal component H of the Earth's magnetic field decreases, especially in low and middle latitudes. It is this decrease that is often used to identify the initial, main and recovery phases of magnetic storms. During strong and persistent disturbances of the Earth's magnetic field, which are called magnetic storms, the *DR* current field intensity is much higher compared with the *DCF* fields, so the decrease in *H* is a characteristic feature of magnetic storms.

2.1. What is *DCF* field?

Explaining the nature of the Earth's magnetosphere, Chapman and Ferraro stressed the existence of a current which flows at its boundary. In their opinion this current entirely shields the geomagnetic field in the near-Earth space, creating a closed cavity called the magnetosphere. The current flowing on the magnetopause is known in the literature as the Chapman-Ferraro (*CF*) current. Consequently, the disturbed magnetic field on the Earth's surface described by the Dst variation was for a long time thought to be the sum of two components: $Dst = DCF + DR$, *DCF* is the magnetic field due to the magnetopause current, screening the geomagnetic dipole, and *DR* is the field due to the ring current. To quantitatively describe the *DCF* field the relationship $DCF = bP^{1/2}$ is used, according to which *DCF* is associated with the solar wind kinetic pressure *P*; the coefficient *b* is defined experimentally. Our knowledge about current systems in the near-Earth space has increased considerably since the pre-satellite era. Based on this, a more accurate relationship than $DCF = bP^{1/2}$ can be derived, though this relationship is still used in modern prediction models of the *Dst* variation and to correct *Dst* by removing the *DCF* field.

The *CF* current must be considered as a real current on the magnetopause, which is a net current system resulting from several sources. The following currents are part of this magnetopause system: current shielding the geomagnetic dipole; current shielding the ring current; current associated with the magnetotail current system; current associated with the high-latitude Region 1 field-aligned currents (FAC); current shielding the remaining currents in the magnetosphere (i.e., *Sq* currents and others, some likely not identified yet). This makes it difficult to estimate the magnetic field produced by the real *CF* current. Keeping in mind this complex system of real magnetopause currents, the relationship used to estimate $DCF = bP^{1/2}$ should be reconsidered. On the one hand, using the paraboloid model (PM) *Alexeev and Feldstein* [2001] estimated the DCF field as a field due to a net current system shielding both the geomagnetic dipole and ring current. On the other hand *Kozyra et al.* [2002] used the relationship **DCF** $= bP^{1/2}$ to estimate this field in their model calculations. The differences between these two estimates of *DCF* (both for the 24-27 September 1998 magnetic storm are discussed in [*Feldstein et al.*, 2005]. The authors consider the amplitudes of the *DCF* field estimated by these two approaches: *DCFPM* due to *CF* currents needed to balance the magnetic field calculated by the PM model and *DCFSWP* calculated as a function of only the solar wind pressure on the magnetosphere. The two model versions of the pressure equilibrium at a magnetopause subsolar point are also considered: quiet conditions for magnetospheric current systems when IMF $Bz > 0$ and disturbed conditions, when IMF $Bz < 0$. By doing this, the authors investigate the pressure balance at the magnetopause subsolar point under the same solar wind dynamic pressure, but different IMF *Bz* conditions: $P(IMF\ Bz > 0) = P\ (IMF\ Bz < 0) = B^2 / 2\mu$, where *B* is the magnetic field intensity at the subsolar point. This field is due to the following sources: geomagnetic dipole, Chapman-Ferraro current, ring current, FAC system, magnetotail current system. The *CF* current is a current on the magnetopause, shielding the fields of the magnetospheric current systems identified above. In the case IMF $Bz > 0$, the magnetospheric *B* field is largely defined by the geomagnetic dipole and corresponding shielding currents. For this case, pressure balance at the subsolar point takes place at the geocentric distance $R1\ (Bz > 0)$. In the case IMF $Bz < 0$, the magnetospheric field *B* has major contributions not only from the geomagnetic dipole and corresponding shielding currents, but also from additional current systems and their shielding currents. The magnetic fields at the subsolar point contain contributions from *FAC* and tail currents which are of opposite direction compared to the geomagnetic dipole field and the field of its shielding currents. This is why pressure balance at the subsolar point takes place at smaller geocentric distance $R1\ (Bz < 0)$ compared to $R1\ (Bz > 0)$. Since the distance $R1\ (Bz < 0)$ is smaller than $R1(Bz > 0)$, the corresponding field of the shielding current on the Earth surface is greater. The estimation of the magnetospheric fields due to *CF* currents using the relationship $bP^{1/2}$ usually means that the solar wind dynamic pressure is balanced only by the magnetic pressure of the Earth's dipole magnetic field. It means that the IMF dependence of the geocentric distance to the magnetopause subsolar point is omitted from consideration. On the contrary, when the PM model is used, the component of the CF current needed to shield the geomagnetic dipole contribution to the subsolar magnetic field is greater for $P(Bz < 0)$ than for $P(Bz > 0)$. This means that the radial distance at which pressure balance was achieved between the solar wind dynamic pressure and the Earth's magnetic field pressure moved to smaller radial distances (larger values of the dipole field component) for IMF $Bz < 0$. Since the solar wind dynamic pressure has not changed, the Earth's subsolar magnetic field must weaken for $P(Bz < 0)$ relative to $P(Bz > 0)$ in the PM. The decrease in magnetic field strength at the subsolar magnetopause cannot be attributed to erosion due to magnetic reconnection, which is not explicitly represented in the PM but rather must be due to other current systems as they respond to IMF $Bz < 0$ conditions. The magnetotail current flowing along the magnetopause boundary is opposite in direction to the *CF* currents and thus weakens the subsolar magnetic field compared to a purely dipolar field at a given magnetopause distance, *R1*. The ring current does not flow along the magnetopause but is contained completely inside the magnetosphere. It weakens the magnetic field within and strengthens the magnetic field outside its edges thus adding a positive contribution at the magnetopause which is weakened by its greater distance. The magnetopause moves inward to find a pressure balance between the solar wind dynamic pressure and the stronger PM magnetic fields at smaller radial distances. The same net *CF* current is now located closer to the Earth and thus produces a larger *DCF* contribution to *Dst*. The differences in *R1* for the same solar wind dynamic pressure but for different magnetic field models (i.e., the PM model field and a dipole field) differ from the empirical fits *R1* by [*Shue et al*., 1997] These differences in approach lead to differences in the amplitudes of DCFPM in [*Feldstein et al*., 2005] and DCFSWP usually used in the literature. The DCFPM field on the Earth's surface is given as follows: *DCFPM = DCF1 + DCF2* where *DCF1* is the magnetic field due to magnetopause currents, shielding the geomagnetic dipole field and *DCF2* is the magnetic field due to currents shielding the magnetic field of the ring current. Both the tail current and FAC flow on the magnetopause as well and do not need their shielding, as contrasted to other current systems which require their shielding to be considered.

2.2. Not *Dst=DCF + DR*, but *Dst =DCF + DR + DT + DP + ……*

The structure of the magnetic field in the magnetosphere depends substantially on the location and intensity of the magnetospheric tail current. There is a contradictory evidence regarding the contributions of various sources to the *Dst* variation of the geomagnetic field, which is the most important index for description of geomagnetic storm characteristics including intensity [*Alexeev et al*., 1996; *Maltsev et al*., 1996; *Turner et al*., 2000; *Liemohn et al*., 2001a, b; *Kozyra et al*., 2002]. It is usually believed now that *Dst* is a superposition of the magnetic fields due to the current on the magnetopause (*DCF*), ring current (*DR*) and magnetotail current (*DT*). The relative contribution of these sources to the *Dst* variation during the storm main phase is a topic for lively scientific discussions today. A range of different views on the importance of magnetotail currents has recently been expressed in the literature. *Alexeevet al*. [1996] and *Maltsev et al*. [1996] propose an approximately comparable contribution of *DR* and *DT* to the *Dst* variations. According to *Turner et al*. [2000] and *Baker et al*.[2001], there is only a 25 % contribution of *DT* to *Dst* during magnetic storms. On the other hand, *Liemohn et al*. [2001a] and *Kozyra et al*. [2002] reported a strong agreement between the modeled *DR* and observed *Dst* fields, which implies a minimal (even no) contribution of *DT* to *Dst* at the maximum of the storm main phase. Such a diversity of results is a consequence of using different magnetic field models, on the one hand, and using different methods to identify the boundary in the inner magnetosphere between the magnetotail current (which produces the *DT* contribution) and ring current (which produces the *DR* contribution), on the other hand. This inner boundary of the magnetotail current is located at 3.5–4.0 Re [*Alexeev et al*., 1996; *Maltsev et al*., 1996], 6 Re [*Turner et al*., 2000], and outside of geosynchronous distance at 6.6 *Re* [*Liemohn et al*., 2001a, b; *Kozyra et al*., 2002]. In addition, there are differences in the representation of the ring current which contributes to magnetic field asymmetry and distortion in the inner magnetosphere. Models by *Alexeev, Maltsev and Tsyganenko 89*, used by *Turner et al.* [2000], do not divide the inner agnetospheric current into separate parts as symmetric and asymmetric ring currents.

In RAM model [*Liemohn et al*., 2001a, b; *Kozyra et al*., 2002] the partial ring current is a major source of the magnetic field and energy in the inner magnetosphere. During a magnetic storm the inner edge of the plasma sheet shifts earthward in response to strong convection electric fields. Plasma sheet populations move along open drift paths deep into and through the inner magnetosphere accessing the dayside magnetosphere. During the course of these drifts, plasma sheet particles are adiabatically accelerated to ring current energies and form a partial ring current. The divergence of current on open drift paths injects current into the ionosphere on the dusk side and draws current out of the ionosphere near-midnight. According to the RAM model during the storm main phase when the convection electric field is strong, the bulk of the ring current ions is moving along open drift paths and therefore the main part of the energy in the ring current is contained in the partial ring current. During a storm recovery phase, when the IMF *Bz* turns northward and the convection weakens, open drift paths are converted to closed ones and the symmetric ring current develops within a region and an energy range where electric field drifts become small compared to gradient and curvature drifts [c.f., *Liemohn et al.*, 2001b]. Higher energy particles, whose magnetic field drifts significantly exceed electric field drifts, do not have convective access from the plasma sheet to the inner magnetosphere but move along closed drift paths that encircle the Earth. However, fluctuations in the large-scale electric and magnetic fields cause these particles to diffuse inward slowly building the high energy tail of the ring current over the course of the storm. The region of the magnetosphere where high energy particles move on closed drift paths without encountering the magnetopause is called the trapping region. The location of the trapping boundary, enclosing this region, depends on particle energy. During a storm recovery phase and magneto-quiet times, when the partial ring current is weak or absent, the boundary between the magnetotail currents and the symmetric ring current flowing within the trapping region should be relatively easy to identify. During the storm main phase when the bulk of the ring current energy is contained in the partial ring current topologically connected to the magnetotail along open drift paths, the transition between magnetotail-like currents that close through the magnetopause and the partial ring current that closes through the ionosphere is more difficult to define. Both the partial ring current and the innermost part of the magnetotail current are located near the plasma sheet inner boundary. The main difference in topology between the magnetotail and partial ring currents is that the partial ring current closes through the ionosphere and the tail current closes through the magnetopause. There are regions in the inner magnetosphere where a portion of current closes through the ionosphere and a portion continues moving outward until it encounters the magnetopause and closes. This ambiguity may contribute to the discrepancy in the estimation of relative contributions of magnetotail and partial/symmetric ring current to the *Dst* index during storms. An important feature of the topology of the magnetotail currents in the PM is the closure of the inner portion of the magnetotail current through the dayside magnetopause. It is connected with the assumption in the PM that magnetic field lines of the magnetotail currents close inside the magnetosphere. This has important consequences for the location of the magnetopause and for the relative contributions of the magnetotail and magnetopause currents to the *Dst* index.

3. Conclusions

In addition to its well-known dependence on the kinetic energy content of plasma in the magnetosphere and on the solar wind dynamic pressure on the magnetopause, the *Dst* index is also affected by the open magnetic flux of the magnetotail, which has a generally minor effect on the value of *Dst* but can significantly influence its time derivative. The empirically determined source term for (*d*/*dt*)*Dst* proportional to VB_s, first derived by [*Burton et al*., 1975] is found to be, within observational uncertainties, completely accounted for by the magnetotail effect from the increase of the open flux as the result of dayside reconnection. The observational uncertainties are of course appreciable, and the possibility cannot be excluded that a part of the empirical source term is not accounted for in this way, but there is no positive evidence for it. If this result is accepted, it follows that the magnetotail effect on *Dst* of the decrease of the open flux resulting from the nightside reconnection is offset (at least approximately) by the effect of increasing plasma energy content, with the further consequence that the rate of energy injection into the ring current must be controlled predominantly by the nightside reconnection and is approximately equal to the rate of decrease of magnetic energy in the magnetotail within a region that extends out to a particular boundary, located about as far from the inner edge of the magnetotail as the inner edge is from the Earth. The simplest interpretation of this result is that the kinetic energy of the ring current plasma is actually being supplied by the flux of magnetic energy from the magnetotail, the particular boundary being identified with the near-Earth magnetic X-line. The principal conclusions concerning *Dst* are the following.. The *Dst* index (corrected for solar wind pressure effects) can be considered a measure exclusively of plasma energy content only on timescales on which the amount of open magnetic flux is not changing; on shorter timescales the magnetotail effects cannot be neglected. The source or injection term of the Burton-McPherron-Russell equation represents the effect of increasing open magnetic flux (and is thus indirectly related to input of energy from the solar wind into the magnetotail); contrary to widespread assumption, it does not directly represent energy injection into ring current plasma. For large values of southward IMF component (Bs) during a magnetic storm main phase, the magnetic field on the Earth's surface calculated in PM due to the DCF current system increases by several dozen nT over that calculated from simple pressure balance between the solar wind and Earth's dipole field. This increase is due to the weakening of the dayside magnetospheric fields by the field-aligned current and by tail current closure which shifts the magnetopause closer to the Earth in comparison with those values calculated without these additional current systems. The ionospheric signature of the transition from adiabatic to non-adiabatic ring current energy ion motions in the magnetosphere (termed the b2i boundary) near midnight MLT shifts earthward from values of (7-9) Re during magneto-quiet intervals to values of (3-4) Re at a magnetic storm main phase maximum. This transition was associated with a high degree of stretching in the equatorial magnetic field configuration. This is assumed to mark the earthward motion of the inner boundary of the magnetotail current system. Fields of the magnetotail current system *DT* in PM contribute substantially to the Dst variation during the storm main phase. They are comparable to the *DR* contribution at this time, but quickly decrease at a storm recovery phase *(DT << DR).* The decay parameter for the tail current system is substantially smaller (the dissipation occurs quicker) than for the ring current.

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