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The Solar Wind Energy Input Rate and Recovery of the Magnetospheric Ring Current during the Last Two Solar Cycles

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Abstract. This study presents the recent results of our calculations of the solar wind energy input rate to the magnetospheric ring current in the main phase of magnetic storms used for simulation of Dst index based on solar wind data. For this purpose we studied the solar wind parameters during the last two solar cycles. We looked for geomagnetic storms and intervals appropriate for calculation of the function of solar wind energy input rate to the ring current. Intense solar and geomagnetic activity that had occurred in October - November 2003 and in July and November 2004 allowed us to find intervals for calculation of the solar wind energy input rate for a wide range of the solar wind electric field. It should be noted that previous calculations of the solar wind energy input rate to the magnetospheric ring current were carried out for values of the solar wind electric field limited up to 16 *mV/m*. Furthermore, during the 22-nd and 23-rd solar cycles there were a lot of small and moderate geomagnetic storms which enabled us to correct the injection functions for the magnetospheric ring current. These calculations show us that, as in the case of small and medium storms, the relationship between rate change of the ring current and Ey-component of the solar wind electric field remains linearly proportional for great Ey values. The behavior of the decay constant τ in the main phase of a geomagnetic storm and its recovery phase is different. For severe storms the characteristic time of the ring current decay is about 15-16 *hours* when its recovery is free from injection and it is about 3.5-6 *hours* when an interplanetary injection takes place.

Keywords: solar wind; magnetosphere; ring current; geomagnetic storms

Introduction

The first algorithm for predicting the ground-based 2.5 *min* Dst index from solar wind parameters was presented by Burton et al. in [1] more than 30 years ago. The three key elements of the model based on the physical mechanisms of the solar wind - magnetosphere interaction were: (1) the rate of energy input to the ring current is proportional to the dawn-to-dusk component of the interplanetary electric field Ey which is zero for electric fields below 0.5 mV/m; (2) an adjustment of the energy input rate for the solar wind dynamic pressure; (3) an exponential decay rate of the ring current of about 7.7 *hours*. Burton et al. in [1] used magnetograms from 12 mid-latitude geomagnetic stations and the interplanetary data were interpolated to 2.5 *min* resolution. But the main relationship of the algorithm between the solar wind (SW) electric field and the rate of energy input to the ring current was not confirmed by Feldshtein et al. in [2], who used the same ground-based 2.5 *min* Dst data. Sizova and Zaitseva in [3] made an attempt to validate the algorithm for predicting the hourly means of the Dst index on the basis of King's interplanetary medium data books. They verified the relationship proposed in [1] on the basis of the hourly means of the Dst index and solar wind data. Sizova and Zaitseva in [3] and Pudovkin et al. in [4, 5] calculated the characteristic lifetime of the ring current and concluded that the characteristic time of the ring current is different during the main and the recovery the phases of magnetic storms. The characteristic time of the ring current in the recovery phase increases with storm intensity and may run from 4 to 20 *h*. The characteristic time of the ring current decay in the main phase is independent of storm intensity and may run from 2 to 6 *h*. The principal magnetospheric ring current dissipation mechanisms for estimation of its characteristic lifetime were studied in these papers too. The values of the characteristic lifetime of ring current decay obtained from experiment and theory were compared. It was concluded that during the main and recovery phase of magnetic storm different mechanisms could play major role in ring current dissipation. The available ion composition data gave the ground to suggest, that the mentioned above characteristic decay times of the ring current could be due to ion composition variations connected with changes in ring current intensity (and respectively its position) during the different storm phases and/or increasing the share of the energetic protons on low L-shells [4]. Algorithms and calculations of Dst, containing some physical regularities deduced from this concept were presented by Sizova and Zaitseva in [3], and by Pudovkin et al. in [4-5]. It was shown that the differences between the calculated and observed Dst values in the model proposed by Burton et al. in [1] can be attributed to all key elements of the algorithm. So, this algorithm and its three elements were reanalyzed later in numerous works and a lot of Dst calculations were carried out using the model and its modifications.

Data analysis

The dependence of the energy input rate to the ring current on solar wind parameters as a main element in Dst simulations for the last two solar cycles was studied in [6, 7]. But only several storms were considered in these works. Here we expand this study over all storms of the last two solar cycles with a particular interest in the high-speed solar wind and great negative Bz IMF values. In our previous works [3-5] we described the disturbed ring current field variations during a storm by the expression (1), which is similar to the equation of Akasofu and Yoshida [8] and to that of Burton et al. [1]:

$$dDR^d / dt = Q^d(t) - DR^d / \tau . \qquad (1)$$

Here DR^d is the ring current field during a geomagnetic storm, Q^d is the rate of energy input to the disturbed ring current, and τ is the ring current decay constant. DR^d may be found using the Dst index as determined from the difference between the disturbed (d) day and quiet (q) day of the H -component records at N mid-latitude stations:

$$Dst = 1/N \sum_{i=1}^{N} (H^d - H^q) = \Delta\overline{H} . \qquad (2)$$

The contribution of the magnetopause current (mp) and the ring current (rc) to Dst can be written as

$$Dst = \overline{Hmp^d} + \overline{Hrc^d} - \overline{Hmp^q} - \overline{Hrc^q} . \qquad (3)$$

We can rewrite equation (3) using the designations of the magnetospheric currents and defining DR^d in (4) and (5) as the field of the ring current formed during geomagnetic storm:

$$Dst = DCF^d + DR^d - DCF^q - DR^q , \qquad (4)$$

$$DR^d = Dst - DCF^d + DCF^q + DR^q . \qquad (5)$$

In these equations $DCF = b \cdot P^{1/2}$ is the current field on the magnetopause; the subscripts "*d*" and "*q*" refer to disturbed and quiet periods of the ring and magnetopause currents respectively, $P(eVcm^{-3})$ is the solar wind dynamic pressure, *b* varies from 0.1- 0.4 $nT \cdot (eV\ cm^{-3})^{-1/2}$. Using formulae similar to (1) and (5) the values of the energy input rate Q to the ring current in selected intervals of magnetic storms during the 20-th and the 21-st solar cycles were calculated and compared with the solar wind electric field Ey up to 12 -16 *mV/m* by Burton et al. in [1], by Sizova and Zaitseva in [3], by Pudovkin et al. in [4, 5], and by O'Brien and McPherron in [6]. Burton et al. in [1] selected 15 intervals of ½-*hour* duration in which the dynamic pressure was constant and compared the rate of the ring current change dDR^d/dt with the Y component of the interplanetary electric field. For positive Ey it was found that:

$$F(E) = 1.26 \cdot 10^{-3} Ey + 1.75 \cdot 10^{-4} , \qquad (6)$$

here F(E) is the energy input rate to the ring current expressed in *nT* per second – Q in our notations, and Ey in *mV/m*. The authors noted also that rapidly oscillating electric fields were not rectified as slowly varying fields were. To incorporate such fields in the algorithm the electric field data were filtered. We suppose that the authors in [2] could not confirm this relation because they did not take into account that calculations of F(E) in the paper of Burton et al. [1] were performed for selected intervals of constant solar wind dynamic pressure. It should be noted that calculation of 2.5 *min* Dst is too cumbersome for studying the ring current -solar wind relationships during the numerous geomagnetic storms within the solar cycles. Because of this, we decided to test an empirical relationship between interplanetary conditions and Dst using standard 1-*hour* Dst data presented in http://swdcwww.kugi.kyoto-u.ac.jp. As already mentioned the algorithm presented in [1] was tested in our works [3-5] for predicting the hourly means of Dst index on the basis of King's interplanetary medium data books. At first, in [3, 4] we studied the usage of different functions to describe the rate of energy input to the ring current: $F1 = B^2 V\sin^4(\theta/2)$ – the energy coupling function proposed by Akasofu in [9], where *B* is the module of the IMF vector, θ is the clock angle between the IMF projection in the Y-Z plane and the Z –axis (in GSM coordinate system); $F2 = B_\zeta V\sin^2(\theta/2)$ is the interplanetary electric field *Em* merging with the magnetosphere, where $B_\zeta = sqrt(Bz^2 + By^2)$ [10]; $F3 = B_\zeta^2\sin^3(\theta/2)\, n^{-1/2}$ – the value proportional to the potential difference across the polar cap produced by the merging field proposed by Pudovkin and Semenov [11]; $F4 = Ey = BsV$, $BsV = |VBz|$ if $Bz < 0$ and $BsV = 0$ if $Bz > 0$ – the azimuthal component of the solar wind electric field proposed in [1,12]; $F5 = |VBy|$ - the function determining the Y-component of the reconnection electric field at Bz IMF close to zero. Furthermore, function $F6 = (0.5\sigma - Bz)V$ – the azimuthal component of the solar wind electric field where the high-frequency component of the IMF modulus variability σ is taken into account was added. Values of $|DR^d|_{max} = Q \cdot \tau$ ($\tau = 6\ h$) for 88 storms were calculated at the moments of ring current maximum intensity when $dDR^d/dt = 0$ in (1). The injection functions at these moments were compared with $|DR^d|_{max}$ values. The results are presented by the following regression equations with correlation coefficients r:

$|DR^d|_{max} = 35.8 + 5.6 \cdot 10^{-4} F1$, r = 0.81 (7)

$|DR^d|_{max} = 2.0 + 14.3 \cdot 10^{-3} F2$, r = 0.86 (8)

$|DR^d|_{max} = 40.4 + 0.8 \cdot 10^{-3} F3$, r = 0.63 (9)

$|DR^d|_{max} = 7.3 + 14.7 \cdot 10^{-3} F4$, r = 0.87 (10)

$|DR^d|_{max} = 52.9 + 5.4 \cdot 10^{-3} F5$, r= 0.26 (11)

$|DR^d|_{max} = 5.6 + 11.7 \cdot 10^{-3} F6$, r = 0.86 (12)

Obviously, out of all presented injection functions, Ey-equation (10)- is the best for describing the energy input rate to the ring current (r = 0.87).

Then we selected 44 two-hour intervals of the ring current development phase during which the DCF field variations did not exceed 5 *nT* and $\sigma <$ Bz when Bz IMF had varied very slowly. The $Q^d = DR^d/dt + DR/\tau$ in the selected intervals were calculated making allowance for the decay time $\tau = 6$ *hours*. The Q^d variations were compared with the injection function $F6 = V \cdot (0.5\sigma - Bz)$ corresponding to the Ey component of the solar wind electric field.

The respective dependence is of the form:

$Q = -3.5 + 4.3(0.5\sigma - Bz) * 10^{-3}$ r= 0.86, (13)

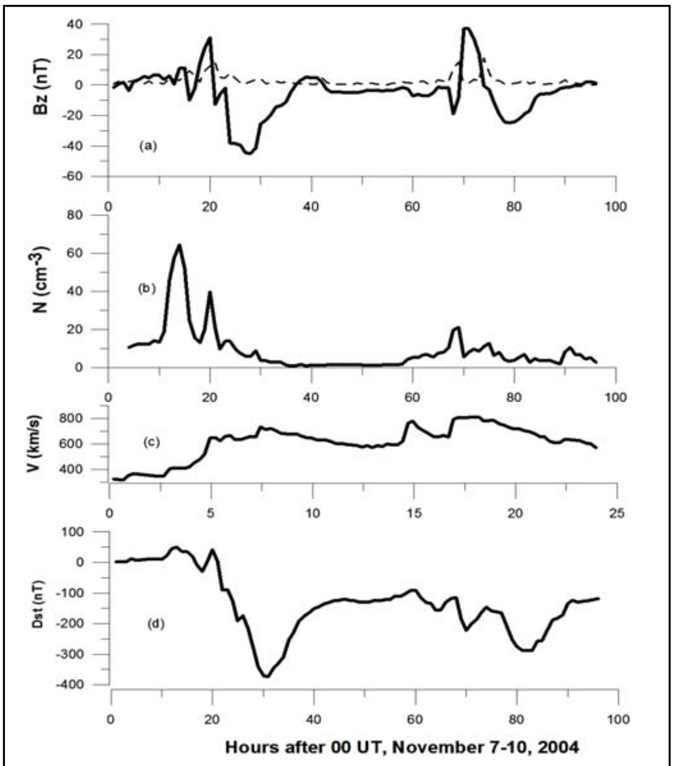

Fig. 1. The solar wind Bz IMF with sigma Bz in nT (panel a), density N in cm^{-3} (panel b), velocity V in km/s (panel c) during the super geomagnetic storm with Dst = - 373 nT on November 7 -10, 2004 (panel d)

here Q is expressed in *nT* per hour, Ey = (0.5σ – Bz) in *mV/m*. Based on the above concepts and making allowance for dependences described by formulae (1-5) and (13), an algorithm for calculating the hourly means of the Dst-variation field on the basis of hourly means of the solar wind parameters was proposed and the Dst field variations for 1200 *hours* were calculated by Pudovkin et al. in [5].

The last two solar cycles allowed us in [13] to test of the rate of energy input Q in a wide range of solar wind electric field values up to 30 *mV/m* because solar wind measurements during severe storms were available. We found that for 26 intervals:

$$Q(Ey) = 1.8V * Bz + 5.5 \qquad r = 0.63 \qquad (14)$$

In this study we continued analysis begun in [13] of the main phases of all geomagnetic storms in the 22nd – 23rd solar cycles and found near 60 intervals with solar wind parameters suitable to study of rate of energy input to the ring current. To calculate Q intervals of strictly stable solar wind parameters and IMF Bz were selected. It should be noted that the Bz IMF stability is a very important condition for calculation of injection rate if we use standard 1-hour average Dst values and this criterion plays the role of a filter. Q is calculated using formulae (1) and (5). In order to compare our results with the results of other authors, we made use of the formula proposed by O'Brien and McPherron in [6]: Dst* = Dst – 7.26P$^{1/2}$ + 11; here Dst* is the disturbed ring current field, DR^{d} in our notation, and this relation is very similar to equation (5). So in our calculations we used DCF^{q} + DR^{q} = 11 *nT*, DCF^{d} = 7.26P$^{1/2}$ *nT* and τ = 6 *hours* for the growth phase of geomagnetic storms. To calculate the energy input rate for large interplanetary electric fields, severe geomagnetic storms as that on November 7 -10, 2004 presented in Fig.1 were used. The content of the panels in Fig.1 is as follows: panel (a) presents the IMF Bz component in nT; panel (b) – SW density *N* in *cm*$^{-3}$, panel (c) – SW velocity *V* in *km/s* and panel (d) - Dst variations retrieved from OMNIweb. The dotted line on panel (a) is the standard deviation σ of IMF B and this parameter was taken into account in selecting intervals for calculations. On 8 and 10 November there were several 2-3 *hours* intervals with relatively steady solar wind parameters and they are used for calculating the rate of energy input to the ring current. The rate of energy input to the ring current in the main phase of geomagnetic storms for 60 selected intervals versus the solar wind electric field is presented on the top panel of Fig. 2. The points near 30 *mV/m* Ey values were calculated using the severe storms in 2000, 2003 and 2004. Furthermore, there were a lot of nice small and moderate geomagnetic storms for calculation the energy input rate for Ey values between 0 and 20 *mV/m*. The respective relation between Q and Ey is:

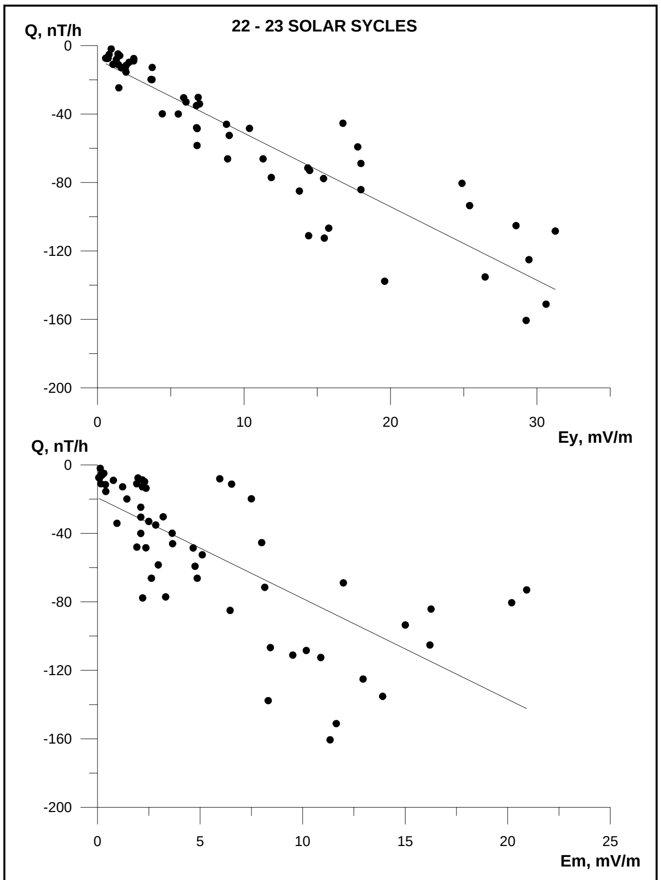

Fig. 2. The rate of energy input to the ring current in the main phase of geomagnetic storms versus the Y component of the solar wind electric field Ey (upper panel) and versus the equatorial merging electric field Em (lower panel) for the 22 and 23 solar cycles.

$$Q(Ey) = -4{,}3 * Ey - 8.2 \qquad r = 0.85, \qquad (15)$$

where *r* is the correlation coefficient.

So, the relationship between the energy input rate to the ring current and the solar wind electric field remains linearly proportional for great geomagnetic storms as well. The rate of energy input to the ring current for negative Ey values was near zero over a wide range. Fig.1 demonstrates this fact: there are no changes in Dst – field before the 7-10 November storm during positive the Bz IMF. Ballatore and Gonzales in [7] have verified the validity of Burton's equation (1) for estimating the ring current energy balance using the equatorial electric merging field Em instead of the dawn-to-dusk component of the interplanetary electric field Ey. Their results indicate that the interplanetary injection is statistically higher than estimations using the solar wind electric field Ey. It should be noted that they presented Em values up to 12 *mV/m*. For our selected intervals in 22-nd – 23-rd solar cycles we have calculated Em according Kan and Lee [10] $Em = VB_{\zeta} \sin^2(\theta/2)$ up to 21 *mV/m*, where B_{ζ} is the projection of the IMF on the Y-Z plane in GSM coordinate system and θ is the clock angle between B_{ζ} and the Z-axis. The rate of energy input to the ring current versus *Em* for the selected intervals during the main phases of geomagnetic storms is presented on the lower panel of Fig. 2.

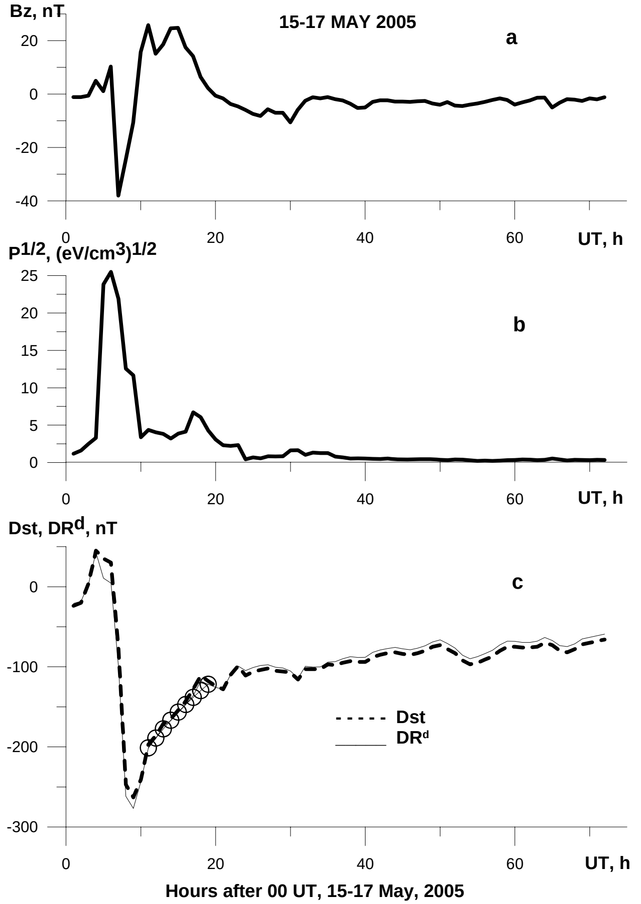

Fig. 3. The solar wind Bz IMF in nT (panel a), the square root of the solar wind dynamic pressure in $(eV/cm^{-3})1/2$ *(panel b), Dst (dashed line) and* DR^d *(solid line) variations during the great geomagnetic storm with* Dst_{min}= -263 *nT on May 15-17, 2005 (panel c). The ring current decay during Bz IMF>0 is denoted by circles on panel c.*

$$Q(Em) = -5.9E*m - 19.1 \qquad r = 0.54 \tag{16}$$

Obviously, this function is also suitable for the Dst predicting at least up to Em = 15 mV/m. But for larger values (see Fig.2) and comparing the correlation coefficients in equations (14) and (15), one can see that Ey (r= 0.85) is much better than Em (r = 0.54).

Recovery phase of geomagnetic storms

Dst variations can be computed from formula (1) using different injection functions Q and knowing solar wind parameters and characteristic time τ of ring current decay. Generally, geomagnetic storms behavior is very complex, especially during their recovery phase, and leads to problems when calculating the characteristic lifetime of the ring current. We have to find intervals when there is no ring current injection during positive Bz IMF and hence it has a little effect on Dst and DR fields. When it is possible to calculate the ring current decay constant from formula (1) we obtain $dDR/dt = - DR/\tau$. But this condition is very rare and the process of pure recovery usually has duration of 1-2 hours. To calculate τ with confidence 3-6 hour intervals are required. The value of τ during storm recovery was found by Pudovkin at al. in [4] from (1) using 3-8 hour intervals when Bz IMF>0 and σ # Bz, i.e. the additional energy input to the ring current could be neglected (σ is the IMF B variability). The analysis of 13 geomagnetic storms provided the base to conclude that the characteristic time of the ring current is different during the main and the recovery phases of magnetic storms. Let us look at the recovery phases of the two storms presented in Fig.1 and Fig.3. We calculated DR^d values for these storms and looked for intervals during their recoveries where there was no ring current injection. When Q = 0, the ring current characteristic time can be calculated as $DR^d = DR^d_0 e^{-t/\tau}$ from (1). On November 8 the interval from 1200 to 1700 UT (around the 40th hour) was suitable for calculation of τ. In Fig.1 one can see that Bz > 0, N and V were nearly constant. We found out from (1) that the characteristic time of the ring current decay for this interval was about 15 hours.

After that followed a long 13 *hours* interval from November 8th till November 9th (between the 40th and 60th hours) when the rate of the energy input to the ring current and its decay were in equilibrium. The average DR^d was about –120 *nT* and Dst changed very little in this interval. The Bz IMF was about –4 *nT* (the electric field was about 2.5 *mV/m* positive) and the dynamic pressure was nearly constant. From equation (1) with the proviso that $dDR^d/dt = 0$ it was possible to calculate τ during stable injection to the ring current during its recovery. From (1) and (15) we found for this storm recovery that *τ = 6 hours*. Following this line of reasoning the characteristic time of the ring current was calculated for the 15-17 May 2005 severe geomagnetic storm presented in Fig.3. For the recovery phase interval between 0900 UT to 1800 UT on 15 May when Bz IMF > 0, Q = 0 and the electric field went negative, we found that τ was about 16 hours. In Fig.3, panel c this interval is denoted by circles. Between 2300 UT on 16 May and 0400 UT on 17 May the ring current decay and injection were in equilibrium. Positive electric field Ey was about 5 mV/m and DR^d was about -100 nT. Under these conditions from (1) and (15) τ was calculated to be about 3.5 hours. The results of calculation of τ during these two geomagnetic storms show that the characteristic time is different when the ring current is free from injection during positive Bz IMF and when injection takes place. Characteristic time of the ring current decay is about 15-16 hours during its recovery free from injection and it is about 3.5-6 hours when an interplanetary injection takes place. These decay times are in agreement with the conclusions of Pudovkin et al. made in [4].

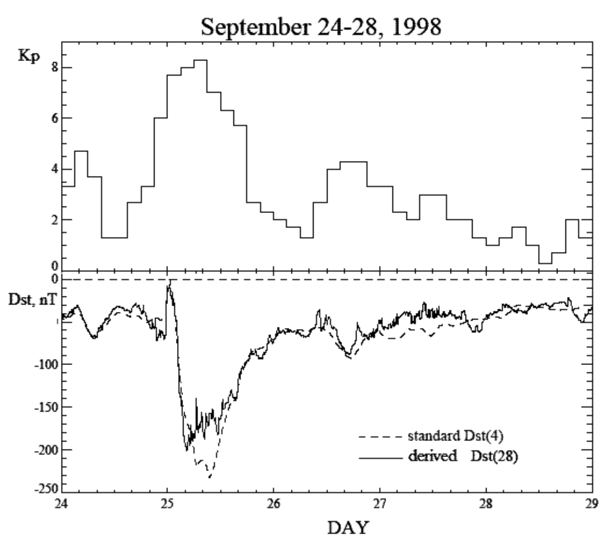

Fig.4. An example of a complex severe geomagnetic GEM storm during the 23rd solar cycle. Top panel- Kp index, bottom panel - 5 min Dst data, calculated from 28 stations - data denoted as measured, and Dst from http://swdcwww.kugi.kyoto-u.ac.jp denoted as standard

From the obtained relationship (15) and characteristic time τ of the ring current during its growth and recovery simple calculation of an hour averaged Dst-variations can be carried out using formula (1) and (5). This facilitates the quick estimation of the Dst index directly from the solar wind data. To explain the difference between 5-min and 1 hour average Dst variations an example of a complex severe geomagnetic GEM storm on September 24-28, 1998 during the 23-rd solar cycle is presented in Fig. 4.

On the top panel is shown the Kp index, and on the bottom panel - the 5 min Dst data derived from 28 stations as retrieved from http://leadbelly.lanl.gov) and Dst variations retrieved from http://swdcwww.kugi.kyoto-u.ac.jp, denoted as standard in GEM storms. We presented here the Kp index to show why this and the other storms in this study are severe storms. According NOAA space weather scale geomagnetic storms are categorized by Kp values. Severe storms have Kp = 8, including 9-, and the number of severe storm events can reach 100 per cycle. During these storms power systems, spacecraft operations and other systems are disrupted, pipeline currents are induced, HF radio propagation is disturbed and aurora is seen up to 45°geomagnetic latitudes. That is why it is important to know how to predict severe storms. As evident from Fig.4 the standard Dst and the derived 5-min resolution Dst vary greatly and the difference between them can reach about 100 nT, especially during severe and strong storms. Consequently, there are differences in calculating the key elements used in the models for prediction of Dst variations from solar wind data and the ring current constants. On one hand 5-min Dst data allow us to find the best intervals for calculating the energy input rate to the ring current and its characteristic time τ, and on the other hand a lot problems arise: estimation of the time delay between geomagnetic and interplanetary data, usage of filtration methods, laboriousness of Dst calculations from great number of geomagnetic stations that is possible during special programs like GEM.

Conclusions

The solar wind energy input rate and recovery of the magnetospheric ring current during 22nd – 23rd solar cycles have been studied.

We have shown that the relationship between the energy input Q and the dawn-to-dusk component of the interplanetary electric field Ey remains linearly proportional even for great Ey values responsible for severe and strong geomagnetic storms.

The use in the energy coupling function of the equatorial electric merging field Em is suitable for the Dst prediction, but for Em greater than 15 mV/m the usage of the dawn-to-dusk component of the interplanetary electric field Ey is much better: the correlation coefficient between the energy input rate Q and Ey is 0.85, while between Q and Em it is 0.54.

The calculation of the characteristic ring current time τ during severe geomagnetic storms shows that it is different when ring current is free of injection during positive Bz IMF and when injection takes place. The characteristic time of the ring current decay is about 15-16 hours during its recovery and it is about 3.5-6 hours when an interplanetary injection takes place.

Within the framework of the different Dst simulation models in order to achieve a better agreement with the observed Dst index we suppose that it would be of particular importance to perfect and verify experimentally the key model elements as characteristic decay time of the ring current, quiet time currents behavior during solar maxima and minima, and variation of the constant for magnetopause currents calculation during severe geomagnetic storm.

OMNI and Dst data used in this study were retrieved from http://omniweb.gsfc.nasa.gov and http://swdcwww.kugi.kyoto-u.ac.jp.

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