International Association of Geomagnetism and Aeronomy (IAGA)
2^{nd} Symposium: Solar Wind – Space Environment Interaction
December 4^{th}–8^{th}, 2009, Cairo, Egypt – L. Damé & A. Hady (eds)

DOI: 10.1012/S120027852014

Solar Wind Energy Input to the Magnetospheric Ring Current

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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 geomagnetic storms used for simulation of Dst index on the basis of the solar wind data. For this purpose we continued studying of the solar wind parameters during the two last solar cycles. We looked for geomagnetic storms in the 22 and 23 solar cycles for calculation of the solar wind energy input rate functions to the ring current. Intense solar and geomagnetic activity in these cycles allowed us to find the acceptable intervals for the wide range of the solar wind electric field when the solar wind energy inputs to the magnetosphere uniformly.

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

1 Introduction

The main mechanism of the solar wind energy transfer to magnetosphere by the interplanetary magnetic field (IMF) Bz component orientation was first proposed by J.W. Dungey [1]. Since that time more than twenty the solar wind-magnetosphere coupling functions were used to study geomagnetic activity and the qualitative empirical and theoretical relations were found between the geomagnetic indices and the solar wind parameters taken individually or in various combinations [2-3]. The models based on these functions make it possible (if there exist some methods for predicting the solar wind parameters) to predict the geomagnetic disturbance level. Observations of the global corona structure and its evolution over the solar activity cycle by Yohkoh, SOHO and Ulysses successful missions promise a significant progress on predicting of the solar wind parameters. Research of coronal mass ejections (CMEs) in the solar wind or interplanetary CMEs (ICMEs) and its characteristics is carried out very actively [4, 5]. For forecasting of geomagnetic conditions for 2-3 days ahead, we have to know that the arriving solar wind structures have a southward magnetic field component. There are to be known also a velocity, density, temperature, composition of the arriving solar wind structures, and its arrival times. A lot of modeling attempts are made to relate the magnetic field structure of the ejecta to that of filaments and the overlying global dipolar field of the Sun. However, there is no systematic scheme to predict the internal structure of CMEs based on magnetograms of the eruption regions which are transformed in consequence of dynamic processes in the interplanetary medium. Thus at this stage one can only estimate of the probability of geomagnetic disturbances. Solar cycle variations and average characteristics of large-scale solar wind structures are cataloged in http://cdaw.gsfc.nasa.gov/CME_list, ftp://ftp.iki.rssi.ru/pub/omni/catalog, Thus compiling of event catalogues are important for a global understanding these phenomena and to estimate its geo effectiveness. In the absence of the IMF and the solar data the geomagnetic storms, on the other hand, can help to identify ICMEs , CIRs (corotating interaction regions) streams and other coronal structures.

Dst is predictable and a very wide used index to study the Earth's magnetospheric currents and for estimation of the solar-terrestrial activity. It is represented in the OMNI database (http://omniweb.gsfc.nasa.gov) alongside with the solar wind data.

Simulation of Dst index on the basis of the solar wind energy input to the ring current and the adjustment for the solar wind dynamic pressure with the exponential decay rate of the ring current has more than thirty year-old history. The first algorithm for predicting the ground-based 2.5 min Dst index from solar wind parameters was presented by Burton et al. in [2]. 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*. It was shown in [6-8] that 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*. Algorithms and calculations of Dst index, containing some physical regularities deduced from this concept were presented. The differences between the calculated and observed Dst values in the model proposed in [2] 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.

In this work 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 (22-23) is studied. Here we expand this study over the storms of the last two solar cycles with a particular interest in the high-speed solar wind and great negative Bz IMF values because the 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*. The characteristics of large-scale solar corona and solar wind structures are inspected for its effects on the magnetospheric ring growth.

2 Data analysis

In our previous works [6-9] 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 [12] and to that of Burton et al. [1]:

$$dDR^d / dt = Q^d(t) - DR^d / \tau \,. \tag{1}$$

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:

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

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

$$Dst = \overline{Hmp^d} + \overline{Hrc^d} - \overline{Hmp^q} - \overline{Hrc^q}\,. \tag{3}$$

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:

$$Dst = DCF^d + DR^d - DCF^q - DR^q\,, \tag{4}$$

$$DR^d = Dst - DCF^d + DCF^q + DR^q\,. \tag{5}$$

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, $P(\mathrm{eVcm}^{-3})$ is the solar wind dynamic pressure, *b* varies from 0.1- 0.4 $\mathrm{nT}\cdot(\mathrm{eV\ cm}^{-3})^{-1/2}$. In [2] were selected 15 intervals of ½-hour duration in which the dynamic pressure was constant. They were compared with the rate of the ring current change dDR^d/dt and the Y component of the interplanetary electric field. For positive Ey it was found that:

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

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*.

In this study we continued analysis the main phases of geomagnetic storms in the 22nd – 23rd solar cycles and found near 60 suitable intervals to study of rate of energy input to the ring current. To calculate Q the strictly stable intervals of 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 [10]: $Dst^* = Dst - 7.26P^{1/2} + 11$; 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 $\tau = 6$ *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 Figure 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 Figure 2. The points near 30 *mV/m* Ey values were calculated using the severe geomagnetic storms in 2000, 2003 and 2004. They are related in the catalogues as CMEs events storms. Furthermore, there were a lot of small and moderate geomagnetic storms for calculation the energy input rate for Ey values between 0 and 20 *mV/m*. These geomagnetic storms are caused by the CIRs, the magnetic clouds (MC) and by the heliospheric current sheet (HCS). The respective relation between Q and Ey is:

$$Q(Ey) = -4,3 * Ey - 8.2 \qquad r = 0.85\,, \tag{7}$$

where *r* is the correlation coefficient.

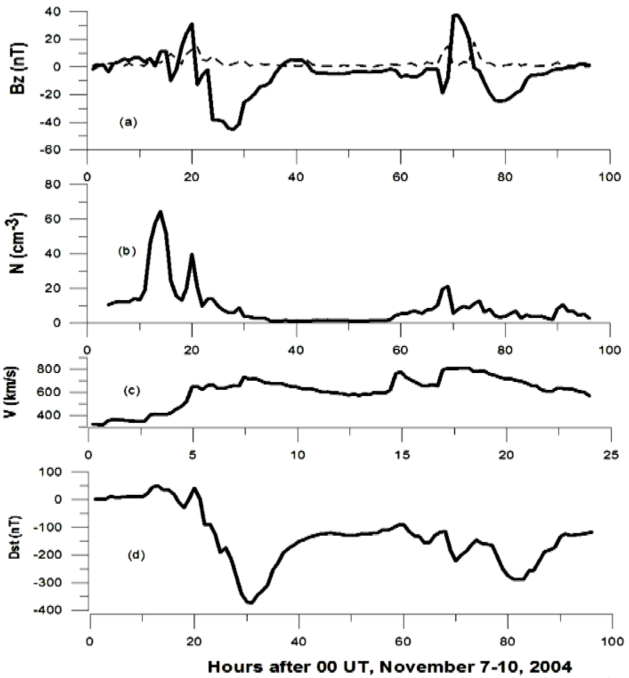

Fig. 1. The solar wind Bz IMF with sigma Bz in nT (panel a), density N in cm^{-3} (panel b), velocity V in km/s (panel c) during the super geomagnetic storm with Dst = - 373 nT on November 7 -10, 2004 (panel d)

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. Figure 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 [11] 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. They concluded 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 [13]: $Em = VB_\zeta sin^2(\theta/2)$ up to 30 *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.

$$Q(Em) = -5.9E*m - 19.1 \qquad r = 0.54 \tag{8}$$

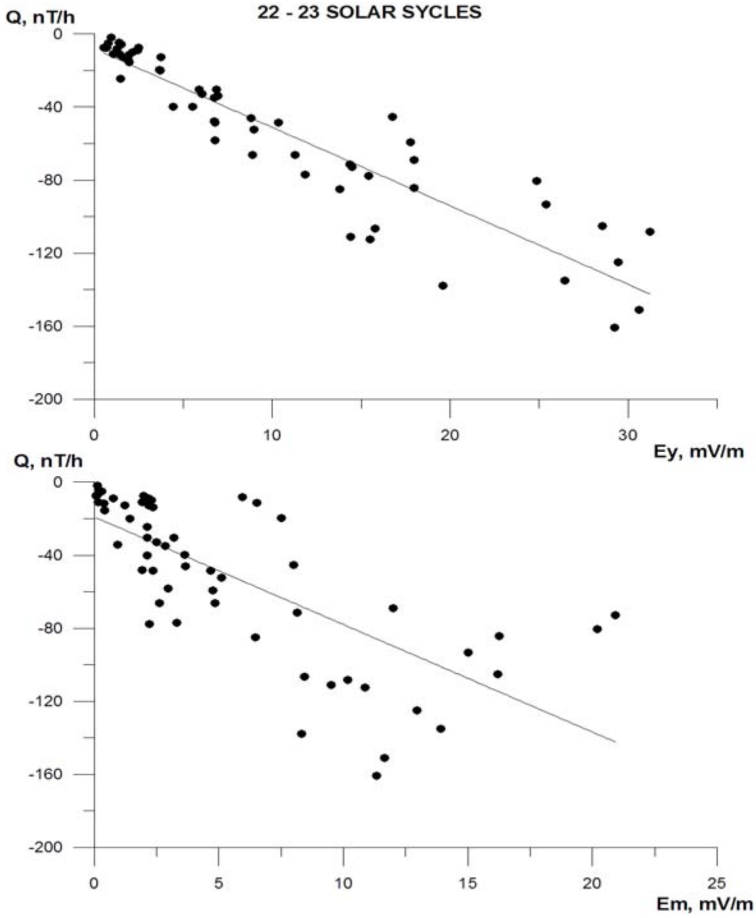

Fig. 2. The rate of energy input to the ring current in the main phase of geomagnetic storms versus the Y component of the solar wind electric field Ey (upper panel) and versus the equatorial merging electric field Em (lower panel) for the 22 and 23 solar cycles.

Obviously, this function is also suitable for the Dst predicting at least up to Em until 15 mV/m. But for larger values (see Fig. 2) and comparing the correlation coefficients in equations (7) and (8), one can see that Ey (r = 0.85) is much better than Em (r = 0.54).

3 Conclusions

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

It is shown that the relationship between the solar wind energy input to the ring current Q and the dawn-to-dask component of the interplanetary electric field Ey remains linearly proportional even for great Ey values which are responsible for severe and strong geomagnetic storms. The energy coupling function Em is suitable for the Dst prediction, but for Em greater than 15 mV/m usage of the dawn-to-dusk component of the interplanetary electric field Ey is much better.

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 (slow streams in the solar wind).

OMNI, CME data used in this study were retrieved from http://omniweb.gsfc.nasa.gov, http://cdaw.gsfc.nasa.gov/CME_list and, ftp://ftp.iki.rssi.ru/pub/omni/catalog/.

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