Symmetric or asymmetric energy transfer from Interplanetary Coronal Mass Ejections to the magnetosphere depending on the solar dipole

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Abstract

The annual behaviour of monthly number of hours spent by the Earth in domains of either positive or negative B_y component of the interplanetary magnetic field (IMF) was studied. We used the hourly OMNI data in the cases of $Kp>3$. The study was confined to the ascending phases of the four recent sunspot cycles when Interplanetary Coronal Mass Ejections (ICMEs) dominate among the sources of geoeffectiveness. Definite differences were found between the annual variations of the hourly sums. When the solar dipole is opposite to the terrestrial one, the sums exhibit the the combined effect of Rosenberg-Coleman and Russell-McPherron effects. Thus, in the geomagnetically active hours the negative B_y dominates during the first half of the year and the positive B_y dominates during the second half of the year. However, these effects can not be detected in the occurrence of the negative and positive GSM B_y values when the solar and terrestrial dipoles are parallel. In this case one can see polarity-independent semiannual variations instead of the polarity-dependent opposite annual variations. It is well-known that the B_y component modulates the energy transfer from the solar wind to the magnetosphere causing marked asymmetries in magnetospheric convective flow pattens at high latitudes. Our results hint that the occurrences of these asymmetries related to the ICMEs depend on the solar dipole cycle. In the antiparallel years one of them dominates during half a year causing asymmetric energy transfer to the magnetosphere. In the parallel years the occurrences of the two kind of asymmetries are equal on monthly time scale, thus the energy transfer is symmetric within a monthly and yearly time interval.

Key words: Interplanetary magnetic field, coronal mass ejection, 22-year cycle, solar-terrestrial relationships

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Preprint submitted to Elsevier Science *22 February 2005*

1 Introduction

The lower atmosphere has a quite complex pattern of responses to the ejected solar plasmas depending on the magnetic topologies of their solar sources. A series of papers (Baranyi et al. 1998 and references therein) has been devoted to the long-term (119 year) impact of solar corpuscular radiation onto the terrestrial troposphere. The main aim of these studies was to detect signatures of solar plasma effects into the troposphere and to clarify the role of plasma processes in affecting the lower atmosphere. These studies revealed 22-year variation of regularities in the specific responses given by the troposphere to those events in which the solar energy was carried by particles. It is a surprising common feature of these effects that the terrestrial response is apparently sensitive to magnetic polarity conditions of solar origin. On the one hand it can distinguish between consecutive cycles of the solar dipole field. On the other hand it can also distinguish between plasmas from the active region belts and the polar coronal holes. The opposite versions of these features are detected in the eastern and western hemispheres, the separating border lies close to the meridian crossing the magnetic pole. These findings are unambiguous signatures of solar plasma effects in the lower atmosphere, and they indicate that the tropospheric response may be sensitive to the differences in magnetic topologies. This means a sensitivity on one hand to the polarity of the main dipole field, on the other hand to the plasmas from dipole as well as multipole fields. This latter distinction separates the polar regions which are the sources of the high speed streams from coronal holes as well as from the active belts which are the sources of Coronal Mass Ejections (CMEs) and their interplanetary counterparts (ICMEs) which are formed by plasma and magnetic fields expelled from the Sun during CMEs (e.g. Crooker, 2000). The chain of mechanisms causing these solar-terrestrial effects is not yet obvious. Study of any effects which are polarity-dependent and dipole-cycle-dependent may contribute to finding any links in the chain.

The primary causes of geomagnetic storms are solar wind structures with intense southward interplanetary magnetic fields, which interconnect with the Earth's magnetic field and allow solar wind energy transport into the Earth's magnetosphere. The solar energy flux density associated with magnetospheric disturbances also depends on the velocity of the wind (Akasofu, 1981). There are two types of interplanetary structures which can cause geomagnetic storms: the ICMEs and the high-speed wind streams (Gonzalez et al., 1999). In order to be able to interpret the above regularities, we should find those features of the incoming plasmas which depend on the solar origin of the ejected plasma and any sort of annual/semiannual run may be relevant. One of our recent papers (Baranyi and Ludmány, 2002) summarizes the known differences between the effects of high speed wind streams and ICMEs. Since that a new fact has been revealed by Vieira et al. (2004), who studied the storm-time ring current evolution of 20 intense magnetic storms. They found that the energy injection rate is different for different interplanetary structures: corotating interaction regions of wind streams as well as different types of ICMEs. This latest result draw the attention to the fact that the differences in the way of the energy transport may play also important role in formation of polarity-dependent solar-terrestrial effects. Our present aim is to study of the dipole-cycle-dependent way of energy transport from ICMEs to the Earth's polar region extending our previous work (Baranyi and Ludmány, 2003a,b).

In order to find the appropriate strategy it is worth making the following considerations. The B_z component of the interplanetary magnetic field determines the rate of energy transfer: when B_z is negative, considerably more energy penetrates into the near-Earth environment than in the case of positive B_z. However, the B_y component can modulate this process, causing marked dawn-dusk asymmetries in magnetospheric convective flow patterns at high latitudes. In the presence of IMF B_y the polar cap (a region in which the terrestrial field lines are magnetically connected to the solar wind) and the auroral oval as a whole is shifted in the direction opposite to B_y in the northern hemisphere and in the same direction as B_y in the southern hemisphere (e.g. Cowley et al. 1991, Khan and Cowley, 2001). This causes dawn-dusk asymmetric energy transfer from the solar wind to the magnetosphere-ionosphere system, and it may also affect the lower atmosphere. In this way, any dipole-cycle-dependent variation of the dawn-dusk asymmetry may cause dipole-cycle-dependent variation of some characteristics of the troposphere. To reveal the possible dipole-cycle-dependent variation of the dawn-dusk asymmetry, we studied some effects of the B_y component of the IMF on geomagnetic activity during ascending phase of the solar cycle when ICMEs are found to be dominant.

2 Russell-McPherron effect and Rosenberg-Coleman effect

The geoeffectiveness also varies on a yearly time-scale. The level of the geomagnetic activity shows semiannual variation characterized by a higher level of geomagnetic indices and higher occurrences of intense storms at about the equinoxes than at the solstices (Cliver and Crooker, 1993; Cliver et al., 2000, 2002). This variation is generally attributed to three mechanisms: Russell-McPherron effect as well as axial and equinoctial mechanisms. The rates of contribution of these mechanisms to semiannual variation are still under debate. Independently from their general rates of contribution, from the point of view of the present work only those effects are important which depend on the polarity of the IMF and the dipole cycle: the Russell-McPherron effect and the Rosenberg-Coleman effect (one of the contributors to the axial mechanism).

The Russell-McPherron effect (R-M effect) is caused by the transformation of the magnetic field vector from the GSE system into the GSM system (Russell and McPherron, 1973). This transformation modifies the value and/or direction of the B_z component depending on the direction of the B_y component. If the magnetic vector lies in the ecliptic plane, the GSM B_z only depends on the GSE B_y. In the first half of the year negative GSM B_z is projected by negative GSE B_y, and positive GSM B_z is projected by positive GSE B_y. In the second half of the year the roles of the GSE B_y components reverse. The annual variation of the GSM B_z projected by the positive GSE B_y (away polarity) is sinusoidal reaching negative extreme after the September equinox. The sinusoidal variation of the GSM B_z projected by negative GSE B_y (toward polarity) takes its negative extreme after the March equinox. Thus, the semiannual variation consists of two opposite annual variations according to the positive and negative B_y. Although the geometrical transformation related to this effect causes always the same projectional effect, the two sinusoidal annual variations may be distorted in all cases. If the magnetic vector has a GSE B_z component, the GSM B_z depends on both the GSE B_y and the B_z. The absolute value of the GSM B_z may be larger or smaller than that of the GSE B_z and their sign may be the same or opposite depending on the actual geometrical situation. In this way the annual variation of the GSM B_z depends on the directions of the magnetic fields of the incoming plasma streams.

As the Earth's heliographic latitude increases, there is a statistical tendency to observe the polarity of the related solar hemisphere (Rosenberg and Coleman, 1969). When the southern pole is negative, at about March the negative polarity of the southern hemisphere reaches the Earth more often than the positive polarity of the northern hemisphere, but the polarity of the northern hemisphere dominates in the second half of the year (Rosenberg-Coleman effect, R-C effect). In this case the dominant polarity is favorable for the R-M effect in both halves of the year. When the southern pole is positive, the dominant polarity is always unfavorable for the R-M effect during the year. The recent results show that the 1 year signal of R-C effect is concentrated around solar minimum and the rising phase (Echer and Svalgaard, 2004).

The components of the interplanetary magnetic fields gathered by several spacecraft since 1963, and *Ap* index data are available in the Near-Earth Heliospheric data set (OMNI). In this era there were three dipole cycles observed from beginning to end. The dipole cycle is called "parallel (P)" if the solar and terrestrial dipole fields are parallel, and it is called "antiparallel (A)" if they have opposite directions. For these intervals the first row of Figure 1 shows the actual manifestations of R-M effect in the annual variations of monthly mean *Ap* index, which shows maxima when GSM B_z has negative extrema. The second row shows the dipole cycle-dependent Rosenberg-Coleman effect in the number of hourly data in which the GSM B_y was negative or positive respectively. In the A years those polarities are dominant which are favorable for the R-M effect and cause higher level of geomagnetic activity. In the

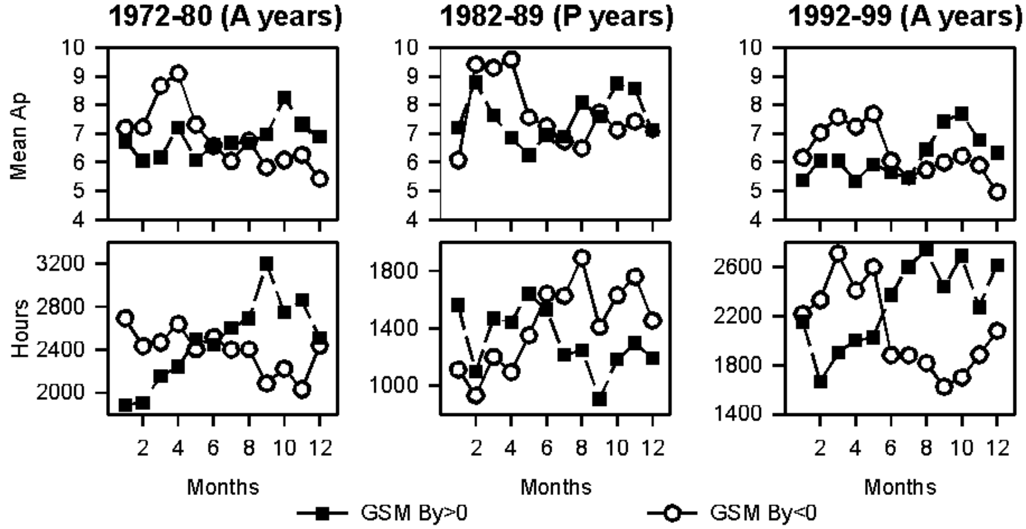

Fig. 1. Annual variation of monthly mean *Ap* index and the number of hours spent in domains of either positive or negative GSM B_y in the given months.

P years the dominant polarities are unfavorable for this effect, and the less frequent polarities cause larger *Ap*.

3 Data sets and results

If one considers mean statistical characteristics of ICMEs during the last four solar cycles, one can use statistical method instead of identification of ICMEs. Richardson et al. (2001) found that the most probable value of *Kp* associated with ICMEs or corotating fast wind streams from coronal holes is about 3. If one wants to study the most probable characteristics of these kind of events, the studied range of *Kp* should contain this peak at least partially. The slow wind usually causes geomagnetically quiet hours ($Kp \sim 1$-2) but sometimes it can be associated with higher *Kp* values. If those hourly IMF data are selected when *Kp* is larger than 3, then the largest part of the effects caused by ICMEs and fast wind streams can be studied. Richardson et al. (2001) also found that during the solar maximum years the ICMEs have the dominant fractions of all occurrences of a given *Kp* if $Kp > 4$. In the range of $3 < Kp > 4$ the fractions of ICMEs and fast wind streams are about equal, and this means that in the range $Kp > 3$ the effects of ICMEs are dominant. During the minimum years the streams dominate in the range $Kp < 7$ so these years are unfavorable for statistical study of ICMEs. In order to study the statistical characteristics of ICMEs, the time intervals of ascending phases of sunspot cycles can be used when the results are thought to refer to ICMEs because of their statistical dominance.

By using this selection criterion we investigated the actual manifestation of the R-M effect in the annual variations of monthly means of B_z of ICMEs in the GSM system depending on the direction of the B_y component as well as the manifestation of R-C effect in the number of geomagnetically active hours (Kp>3) of ICMEs in domains of either positive or negative B_y. In the OMNI era there are four ascending phases defined by the years after sunspot minimum and before the polar reversal as follows: 1966-68 (P years); 1977-80 (A years); 1987-89 (P years); 1997-99 (A years). For all these intervals we selected the hourly data when Kp>3, and separated them into two subsets for the positive and negative directions of GSM B_y.

Figure 2 shows the results for the ICMEs, which are somewhat different from the well-known results presented in Figure 1. The first row of Figure 2 shows the annual variation of the monthly mean GSM B_z by separating the periods of positive and negative GSM B_y in the case of Kp >3. One can see that during P years the two opposite annual variations according to the R-M effect are much more perceivable than during A years. This means that the rate of energy transfer from ICMEs to the Earth's environment is roughly equal in the case of GSM B_y <0 events and in the case of GSM B_y >0 events during the A years. However, it has a marked dawn-dusk asymmetry during the P years, when much more energy is transferred in the case of the polarity favorable for the R-M effect. The second row displays the number of geomagnetically active hours (Kp>3) spent in domains of either positive or negative B_y during the whole interval. In the A years one can see the same two opposite annual variations as in the second row of Figure 1, although in this case the study is constrained to the geomagnetically active hours. However, the constraint leads to a perceivable change in the parallel years, because this type of annual variation cannot be seen because in about one half of the active hours the B_y is positive and in the other half it is negative in each season. This means that in the P years the energy transfer is well-balanced between the dawn and dusk sides on monthly time-scale, but in the A years it has a marked dawn-dusk asymmetry dominated by one of the polarities.

4 Discussion

We found that in the antiparallel years the dominant location of the energy transfer from ICMEs shows dawn-dusk asymmetry while the mean GSM B_z values are similar for both polarities. As the mean bulk speed is also similar for both polarities of IMF (Baranyi and Ludmány, 2003a), this means that the mean rate of energy transfer is symmetric in the dawn-dusk direction, but the dominant location shows marked dawn-dusk asymmetry according to the dominant polarity. In the parallel years the polar cap is shifted as frequently in the dusk direction as in the dawn direction, so the energy transfer

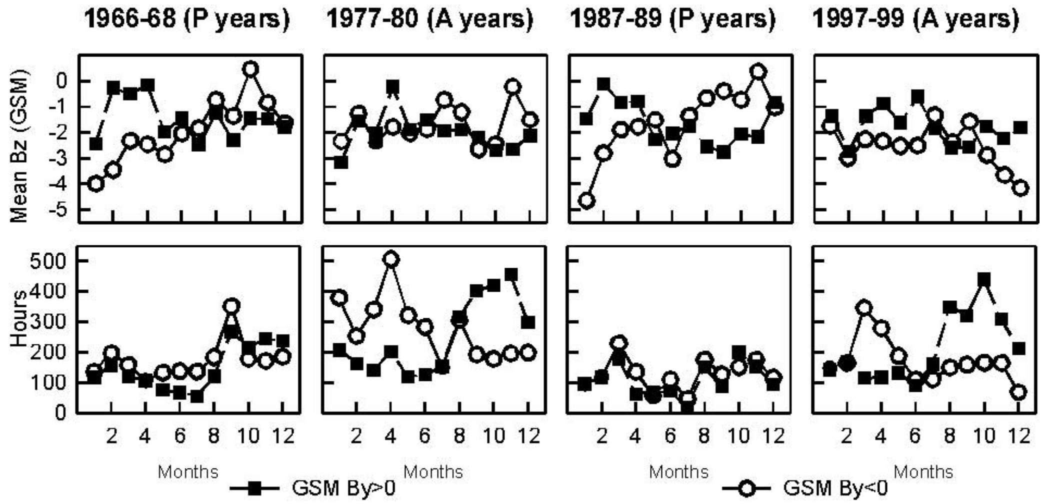

Fig. 2. Annual variations of monthly mean GSM B_z and the number of hours spent in domains of either positive (square) or negative GSM B_y (circle) during the ascending phase of sunspot cycle if $Kp>3$.

is symmetric from the point of view of the location. However, the amount of the energy transferred from ICMEs to the Earth's magnetosphere is larger when the polarity is favorable for the R-M effect, so the rate of the energy transfer shows dawn-dusk asymmetry.

These asymmetries may play an important role in 22-year modulation of terrestrial effects of ICMEs, and it may explain among other things the dipole-cycle-dependent semiannual variation of correlation between ICME-related *aa* index and temperature (Baranyi and Ludmány, 1997). These asymmetric effects of ICMEs may affect the lower atmosphere due to their modulation of the global electric circuit (Tinsley, 2000). According to Tinsley's model the linkage between the solar particles and atmospheric circulation may be the change in J_z air-Earth electric current density at higher latitudes, where relatively large potentials are superimposed on the low latitude value. The dawn-dusk potential in the polar cap region is determined by the GSM B_z and the solar wind velocity. This potential is high on the dawn side and low on the dusk side, but the ratio of the areas of dawn and dusk regions depends on GSM B_y. In this way the averages of the potential over large areas around the geomagnetic pole vary with GSM B_y which also causes a variation of J_z (Tinsley and Heelis, 1993). The polar cap potential variations imply variations in J_z in this region (Tinsley et al., 1998) affecting the microphysical processes in clouds (Tinsley, 2000). This or another similar mechanism may forward the effect of dipole-cycle-dependent variation of the dawn-dusk asymmetry toward the troposphere.

5 Acknowledgments

We thank the two referees for their useful comments. The OMNI data were provided by the NSSDC. This work was supported by OTKA T037725 grant of the Hungarian Scientific Research Fund.

References

[1] Akasofu, S.-I., Energy coupling between the solar wind and the magnetosphere, Space Sci. Rev., 28, 121-190, 1981.

[2] Baranyi, T. and Ludmány, A., Some polarity conditions in corpuscular events. Solar Phys., 173, 383-389, 1997.

[3] Baranyi, T., Ludmány, A., Geoeffective factors of solar plasma streams, Proc. 10th European Solar Physics Meeting, ESA SP-506, 109-112, 2002.

[4] Baranyi, T., Ludmány, A., Effects of solar polarity reversals on geoeffective plasma streams, J. Geophys. Res., 108 (A5), 1212, doi:10.1029/2002JA009553, 2003a.

[5] Baranyi, T., Ludmány, A., Semiannual behaviour of monthly mean of B_z component of geoeffective ($Kp > 3$) coronal mass ejections, in: Proc. ISCS 2003: Solar variability as an input to the Earth's environment, ESA SP-535, 563-566, 2003b.

[6] Cliver, E.W., Crooker, N.U., A seasonal dependence for the geoeffectiveness of eruptive solar events, Sol. Phys., 145, 347-357, 1993.

[7] Cliver, E.W., Kamide, Y., Ling, A.G., Mountains versus valleys: Semiannual variation of geomagnetic activity J. Geophys. Res., 105, 2413-2424, 2000.

[8] Cliver, E.W., Kamide, Y., Ling, A.G., The semiannual variation of geomagnetic activity: phases and profiles for 130 years of aa data J. Atmos. Sol.-Terr. Phys., 64, 47-53, 2002.

[9] Cowley, S.W.H., Morelli, J.P., Lockwood, M., Dependence of convective flows and particle precipitation in the high-latitude dayside ionosphere on the X and Y components of the Interplanetary Magnetic Field, J. Geophys. Res., 96, 5557-5564, 1991.

[10] Crooker, N.U., Solar and heliospheric geoeffective disturbances, J. Atmos. Solar-Terr. Phys., 62, 1071-1085, 2000.

[11] Echer, E., Svalgaard, L., Asymmetry in the Rosenberg-Coleman effect around solar minimum revealed by wavelet analysis of the interplanetary magnetic field polarity data (1927-2002), Geophys. Res. Lett., 31, L1280.1029/2004GL020228, 2004.

[12] Gonzalez, W.D., Tsurutani, B.T., Clua de Gonzalez, A.L., Interplanetary origin of geomagnetic storms, Space Sci. Rev., 88, 529-562, 1999.

[13] Khan, H., Cowley, W.H., Effect of the IMF B_y component on the ionospheric flow overhead at EISCAT: observations and theory, Ann. Geophys., 18, 1503-1522, 2001.

[14] Richardson, I.G., Cliver, E.W., Cane, H.V., Sources of geomagnetic storms for solar minimum and maximum conditions during 1972-2000, Geophys. Res. Lett., 28, 2569-2572, 2001.

[15] Rosenberg, R.L., Coleman, P.J. Jr., Heliographic latitude dependence of the dominant polarity of the interplanetary magnetic field, J. Geophys. Res., 74, 5611-5622, 1969.

[16] Russell, C.T., McPherron R.L., Semiannual variation of geomagnetic activity, J. Geophys. Res., 78, 92-108, 1973.

[17] Tinsley, B.A., Influence of solar wind on the global electric circuit, and inferred effects on cloud microphysics, temperature, and dynamics in the troposphere, Space Sci. Rev., 94, 231-258, 2000.

[18] Tinsley, B. A., Heelis, R. A., Correlation of atmospheric dynamics with solar activity: Evidence for a connection via the solar wind, atmospheric electricity, and cloud microphysics, J. Geophys. Res., 98, 10375-10384, 1993.

[19] Tinsley, B. A., Liu, W., Rohrbaugh, R. P., Kirkland, M., South pole electric field responses to overhead ionospheric convection , J. Geophys. Res. 103, 26137-26146. 1998.

[20] Vieira, L.E.A., Gonzalez, W. D., Echer, E., Tsurutani, B. T., Storm-intensity criteria for several classes of the driving interplanetary structures, Solar Phys., in press, 2004.