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Possible north–south asymmetry related to the mean B_z of interplanetary coronal mass ejections

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Abstract

The annual/semiannual behaviour of monthly mean of B_z component of interplanetary magnetic field (IMF) separated by positive and negative B_y components were studied. The study was confined to the ascending phases of the four recent sunspot cycles when interplanetary counterparts of coronal mass ejections (ICMEs) dominate among the sources of geoeffectiveness. Definite differences were found between the annual variations of the monthly mean B_z values of geoeffective ($Kp > 3$) ICMEs. When the solar dipole is parallel to the terrestrial one, the Russell–McPherron effect is detectable in the opposite annual variations of the mean GSM B_z as is expected. However, when the solar and terrestrial dipoles are antiparallel, the mean B_z does not exhibit the Russell–McPherron effect in the GSM (Geocentric Solar Magnetospheric) system because there are strong inverse annual variations in the GSE (Geocentric Solar Ecliptic) system. This kind of smaller minima of the curves of mean GSE B_z during the antiparallel years indicate that the ICMEs may have much stronger negative GSE B_z values during these years. The southern excess may come from the large-scale north–south asymmetries of the heliospheric magnetic field or from the characteristics of magnetic clouds (direction of the axial field or polarities of the leading and trailing fields).

Keywords: Interplanetary magnetic field; Coronal mass ejection; 22-year cycle

1. Introduction

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. There are two types of interplanetary structures which can cause geomagnetic storms: the coronal mass ejections (CMEs) and the high-speed wind streams (Gonzalez et al., 1999). The ICMEs are interplanetary structures formed by plasma and magnetic fields that are expelled from the Sun during CMEs (e.g. Webb, 2002). The decisive factors in their geoeffectiveness are the intensity and the duration of the southward component of the IMF (B_s), i.e. the negative B_z component in the GSM system. The intense B_s may be a projection of the internal field of CME ejecta or may be formed in the shock and/or sheath region of solar wind ahead of the ejecta caused by the interaction of CME with the surrounding interplanetary field. The geomagnetic *Kp* and *Dst* indices respond differently to disturbances caused by different drivers: shock and sheath, shock and CME, CME ejecta alone, or streams with no shock nor ejecta associations (Huttunen et al., 2002) showing that the intensity of a storm and its variation in time depends on the structure reaching the Earth. The magnetic clouds are especially geoeffective ICMEs. Their most impressive signature is the smooth rotation of the magnetic field direction over a large angle, which results in a substantial and sustained B_s in a part of its transit time. Different levels of geomagnetic activities have different occurrence percentages due to different cloud field: sheath, the leading, the axial, the trailing field, and their combined effects (Zhang et al., 2004).

It is well known that the large-scale structure of the heliospheric magnetic field mainly depends on the direction of the solar main dipole, i.e. on the dipole cycle. When the

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solar north pole is positive, the direction of IMF is away from the Sun above the heliospheric current sheet, and it is toward the Sun under that. If the solar dipole reverses at about the sunspot maximum, the away and toward polarities of IMF are connected to the other poles. The high-speed wind streams coming from the polar coronal holes are obviously governed by the dipole cycle, but the orientation of the main dipole also has a dominant effect on the ICMEs (Crooker, 2000). The north–south asymmetry of dipole cycle may result in large-scale and small-scale asymmetries of the interplanetary magnetic field. At present the most known asymmetry is that the dominant direction of the leading field of magnetic clouds follows that of the large-scale dipole (Bothmer and Rust, 1997; Bothmer and Schwenn, 1998; Mulligan et al., 1998, 2000). Li and Luhmann (2004) found that the predominance of the magnetic cloud polarity reverses within the later part of the declining phase near the solar minimum, showing that both dipole cycle and the active region polarity cycle may affect the magnetic cloud polarity. Our aim is to search for other asymmetries depending on the dipole cycle related to ICMEs extending our previous work (Baranyi and Ludmány, 2003a,b).

2. Selection of ICMEs

Recently several statistical investigations of ICMEs have become available thanks to the new group of satellites: SOHO, WIND, ACE (e.g. Cane and Richardson, 2003; Lynch et al., 2003; Zhang et al., 2004). However, on the longer time-scale the number of available data of identified ICMEs or magnetic clouds is quite low. For example, Mulligan et al. (1998) identified 56 magnetic clouds during 1979–1988 using PVO data. In comparison, Zhang et al. (2004) used a list of 104 clouds observed by WIND and ACE between 1998 and 2001. It is plausible to assume that the occurrence rate of magnetic clouds did not change to such a large extent but the observational technique was improved during the last decade. The case may be similar in the case of non-cloud ICMEs.

By studying the average statistical characteristics of ICMEs during the last four solar cycles one can use another method instead of the identification of ICMEs. The components of the interplanetary magnetic fields gathered by several spacecraft since 1963, and Kp index data are available in the Near-Earth Heliospheric data set (OMNI). Richardson et al. (2001) found that the most probable value of Kp associated with CMEs or corotating fast wind streams from coronal holes is about 3 while the slow wind usually causes geomagnetically quiet hours ($Kp \sim 1$–2). If those hourly IMF data are selected when Kp is larger than 3, then the largest part of the effects caused by ICMEs or fast wind streams can be studied. In order to study the characteristics of ICMEs, the time intervals of ascending phases of sunspot cycle can be used when the effects of ICMEs dominate over the effects of fast wind (Richardson et al., 2001). Thus, we can use the three-hourly Kp index to separate the geomagnetically active hours associated mainly with ICMEs. This method has advantages and disadvantages in comparison with the identification technique. Its advantages are that a large statistical sample can be gathered including the small and hardly identifiable ICMEs. Its disadvantages are that the separation of ICMEs and fast wind streams is not perfect, and the different regions of ICMEs can not be studied separately. However, the largest problem is that the selection of ICMEs cannot be independent from the Geocentric Solar Magnetospheric (GSM) system and the Russell–McPherron effect (R–M effect) if one wants to compare the ICMEs independently from their terrestrial effects.

The Russell–McPherron 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 depends only 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 role of the GSE B_y components reverses. 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. This effect makes the interpretation difficult when the results derived in the GSM system are transformed back to the GSE system.

3. Data sets and results

In this study we investigated the annual variations of monthly means of B_z in the GSM and GSE systems depending on the direction of B_y component. 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. In the OMNI era there are four ascending phases defined by the years after sunspot minimum and before the polar reversal as follows: 1966–1968 (P years); 1977–1980 (A years); 1987–1989 (P years); 1997–1999 (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. In this way, we can investigate the actual manifestation of the R–M effect. Although the geometrical transformation related to this effect causes always the same projectional effect, the two annual variations may not be perceived in the same form in all the 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, and it may reveal some polarity-dependent characteristic features of ICMEs. The small fraction of fast wind streams does not distort the result because their monthly means of B_z are about zero (Baranyi and Ludmány, 2003a).

The first row of Fig. 1 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. The second row displays the monthly mean GSE B_z values for the same events. (In order to be able to study the mean GSE B_z for the same set of events, we have to leave the selection criteria unchanged. Thus, the data set should remain divided into two subsets according to the sign of GSM B_y. In this way, the mean GSM B_z and mean GSE B_z values refer to the same events. If we change the criteria by using the sign of the GSE B_y, a small part of the cases gets from its original subset into the other one and vice versa, which confuses the results. However the result does not practically change if we select only those cases when the signs of GSE B_y and GSM B_y are the same (Baranyi and Ludmány, 2003b).) Two definite opposite annual variations of mean values can be seen in the A years but this pattern is weak in P years. In the A years it is remarkable that the means of GSE B_z are much more negative for that direction of B_y which is unfavorable for the R–M effect in the given season. In the A years the minima reach the values around −4 and −5 while in the P years they are around −2 and −3. This pattern hints at a southern excess of mean GSE B_z during A years in comparison with the mean GSE B_z during P years at least in the case of unfavorable polarities. (Unfortunately this method does not allow to draw any conclusions for the favorable polarities because the R–M effect keeps the mean GSE B_z values around zero.) It was shown for A years (Baranyi and Ludmány, 2003b) that in geoeffective events during unfavorable B_y polarities the percentage of GSE $B_z < -5$ nT events substantially increased while this percentage is roughly equal for both polarities in P years. This also supports the assumption of the southern excess of GSE B_z in the A years.

The differences between the parallel and antiparallel years can be seen much more clearly if we make a further restriction to the hours of negative GSM B_z (by keeping the $Kp > 3$ criterion). The Kp values are averages for 3-h intervals during which the hourly mean of GSM B_z may vary between less effective positive values and geoeffective negative values but the negative subintervals may raise the level of Kp above the selected threshold. Thus, the restriction to the really geoeffective cases decreases the level of noise in the data set. Fig. 2 shows the monthly means of GSE B_z if GSM B_z is negative. These curves show properties of plasma streams in the GSE system when they have negative B_z in the GSM system. In this figure a virtually inverse Russell–McPherron pattern is perceivable in both antiparallel and parallel years but the minima of the curves of B_z are much smaller during the antiparallel years (about −6 and −7) than in the parallel years (about −4 and −5). This confirms the previous result supporting the assumption of the southern excess of GSE B_z in the antiparallel years.

4. Possible reasons of the found asymmetry

As the R–M effect does not depend on the dipole cycle, we may conclude that the cause of the dipole-cycle-dependent asymmetry of annual variation of mean GSE B_z comes from some kind of north–south asymmetry related to ICMEs. The southern excess of mean GSE B_z during the antiparallel years may come from an already known north–south asymmetry of large-scale or small-scale magnetic fields or may refer to a new type of asymmetry. The following explanations may arise at present:

(1) Mursula and Hiltula (2003) found that the average heliospheric current sheet (HCS) is systematically shifted

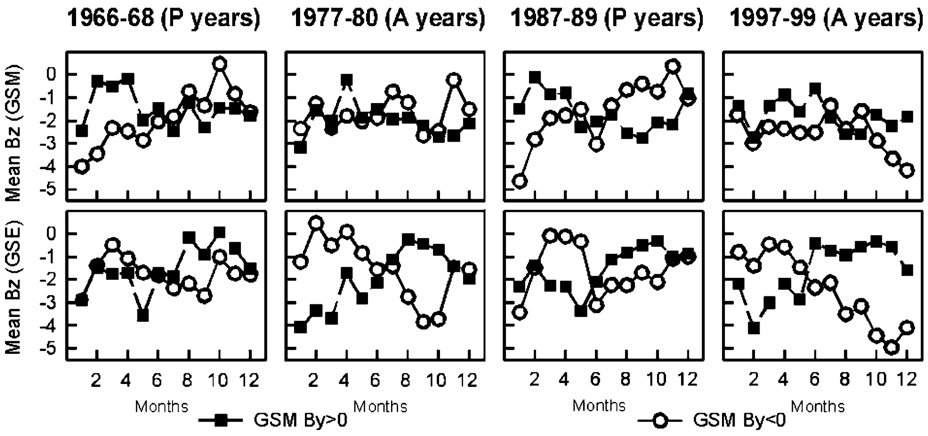

Fig. 1. Annual variations of monthly mean B_z in the GSM and GSE systems, if GSM B_y either positive (square) or negative (circle) and $Kp > 3$ during the ascending phase of sunspot cycle.

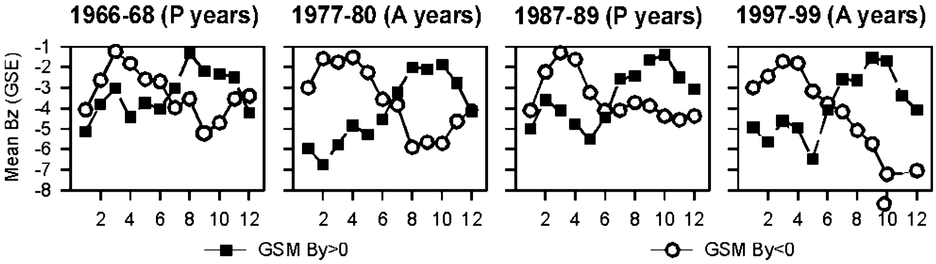

Fig. 2. Annual variations of monthly mean GSE B_z during the ascending phase of sunspot cycle if GSM $B_z < 0$, GSM B_y is either positive or negative, and $Kp > 3$.

or coned southward during solar minimum times. This implies that the open solar magnetic field has a north–south asymmetry at these times, suggesting that the solar dynamo has an asymmetric component. The behaviour of the HCS is different from the north–south asymmetry of streamer belt (Mursula et al., 2002) which is systematically shifted toward the northern magnetic hemisphere. Thus, during negative solar minima the HCS and the streamer belt are both shifted toward the heliographic South. However, during positive solar minima they are oppositely shifted, the HCS southward and the streamer belt northward. At present it cannot be excluded that the asymmetry described in this paper is caused by this type of large-scale asymmetry of the heliosphere.

(2) It is also possible that the asymmetry presented here may be caused by a dipole-cycle-dependent variation in the magnetic configuration of ICMEs. The southern excess of mean GSE B_z in antiparallel years may come from the dominantly southward leading field of magnetic clouds at this time. Zhang et al. (2004) found that different regions of SN, NS, S, and N clouds are differently efficient. Although the geoeffectiveness is not found to be significantly different for SN and NS clouds (Li and Luhmann, 2004; Zhang et al., 2004) but the different mean B_z of the different regions and their different percentages of occurrence may result in slightly different monthly mean B_z values in the antiparallel and parallel years. This question can be decided if the further study planned by Zhang et al. (2004) concerning the statistical differences in B_z strength and longevity observed in the different parts of magnetic clouds will be published. In addition, more samples of magnetic clouds of different time intervals are needed for conclusive statistics.

(3) Zhao and Hoeksema (1998) and Zhao et al. (2001) found that the duration and intensity of the southward IMF within magnetic clouds correlate linearly with the ecliptic latitude of the clouds' central axial field. If there is a north–south asymmetry in the occurrence of different latitudes, this would mean an existence of a dominant direction of the central axial field. Although they found that the magnetic cloud central axial field directions are almost evenly distributed between −90 and 90 degree ecliptic latitude, this result may not be decisive because of the small data set covering different types of time-intervals. The latest study by Lynch et al. (2003) is based on a much larger data set of 56 clouds observed by the ACE spacecraft between February 1998 and July 2001 during the ascending and maximum phases of the last antiparallel dipole cycle. Their histogram distribution of the model parameter of cylinder axis orientation with respect to the ecliptic shows a dominant southern direction of the axial field. This dominantly southern axial field direction is consistent with the sense of the solar dipole field at this time. If the statistically dominant axial field direction reverses with the polarity reversal, the dominant southern axial field may result in southern excess of mean B_z in the antiparallel years in comparison with the parallel years of the dominant northern axial field. This hint needs further study when a well-observed time-interval of parallel years is available.

5. Conclusion

This work focused on the dipole-cycle-dependent manifestation of the R–M effect in the case of geoeffective ($Kp > 3$) ICMEs. We investigated the annual variation of monthly means of B_z component depending on the GSM B_y according to the R–M effect. In the parallel years the mean GSM B_z values show two opposite annual variations according to the R–M effect but this effect cannot be observed in the annual variations of mean GSM B_z in the antiparallel years. The probable reason of the difference is the stronger inverse annual variation of mean GSE B_z because of the more negative intrinsic B_z component of the plasma clouds in the antiparallel years. The minimum values of mean GSE B_z of unfavorable polarities are systematically smaller with 1–2 nT in the antiparallel years. The more negative mean GSE B_z values hint at a southern excess of GSE B_z in the antiparallel years. This may refer to the dipole-cycle-dependent north–south asymmetry related to ICMEs which may come from the large-scale asymmetry of the heliosphere, or the different percentage of occurrence of different types of ICMEs, or the possible dominant central axial field direction of ICMEs. The interpretation of the results and the exploration of their causes need data of original ICME properties in the GSE system but without these data the selection can only be made in the GSM system (where the Kp is defined) and here the R–M effect modifies the mean B_z. Thus, our possibilities to draw conclusions are restricted and the explanation of the results will need another approach in a later study. It is remarkable, however, that the found trends are consistent in the independent time intervals, which raises interesting questions concerning a possible N–S asymmetry related to ICMEs. These questions are worth studying further by using databases of different solar wind components classified on the basis of their interplanetary characteristics.

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References

Baranyi, T., Ludmány, A. Effects of solar polarity reversals on geoeffective plasma streams. J. Geophys. Res. 10 (A5), 1212, doi:10.1029/2002JA009553, 2003a.

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, Tatranska Lomnica, Slovak Republic, ESA SP-535, 563–566, 2003b.

Bothmer, V., Rust, D.M. The field configuration of magnetic clouds and solar cycle. AGU Geophys. Monogr. 9, 139–146, 1997.

Bothmer, V., Schwenn, R. The structure and origin of magnetic clouds in the solar wind. Ann. Geophys. 16, 1–24, 1998.

Cane, H.V., Richardson, I.G. Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002. J. Geophys. Res. 108 (A4), 1156, doi:10.1029/2002JA009817, 2003.

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

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

Huttunen, K.E.J., Koskinen, H.E.J., Schwenn, R. Variability of magnetospheric storms driven by different solar wind perturbations. J. Geophys. Res. 107 (A7), 1121, doi:10.1029/2001JA900171, 2002.

Li, Y., Luhmann, J. Solar cycle control of the magnetic cloud polarity and the geoeffectiveness. J. Atmos. Sol.-Terr. Phys. 66, 323–331, 2004.

Lynch, B.J., Zurbuchen, T.H., Fisk, L.A., Antiochos, S.K. Internal structure of magnetic clouds: Plasma and composition. J. Geophys. Res. 10 (A6), 1239, doi:10.1029/2002JA009591, 2003.

Mulligan, T., Russell, C.T., Luhmann, J.G. Solar cycle evolution of the structure of magnetic clouds in the inner heliosphere. Geophys. Res. Lett. 25, 2959–2963, 1998.

Mulligan, T., Russell, C.T., Luhmann, J.G. Interplanetary magnetic clouds: statistical patterns and radial variations. Adv. Space Res. 26, 801–806, 2000.

Mursula, K., Hiltula, T. Bashful ballerina: Southward shifted heliospheric current sheet. Geophys. Res. Lett. 30 (22), 2135, doi:10.1029/2003GL018201, 2003.

Mursula, K., Hiltula, T., Zieger, B. Latitudinal gradients of solar wind speed around the ecliptic: systematic displacement of the streamer belt. Geophys. Res. Lett. 29 (15), 1738, doi:10.1029/2002GL015318, 2002.

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.

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

Webb, D.F. CMEs and the solar cycle variation in their geoeffectiveness, in: Proc. SOHO 11 Symp., ESA SP-508, 409–419, 2002.

Zhang, J., Liemohn, M.W., Kozyra, J.U., Lynch, B.J., Zurbuchen, T.H. A statistical study of the geoeffectiveness of magnetic clouds during high solar activity years. J. Geophys. Res. 109, A09101, doi:10.1029/2004JA010410, 2004.

Zhao, X.P., Hoeksema, J.T. Central axial field direction in magnetic clouds and its relation to southward interplanetary magnetic field events and dependence on disappearing solar filaments. J. Geophys. Res. 103, 2077–2083, 1998.

Zhao, X.P., Hoeksema, J.T., Marubashi, K. Magnetic cloud B_s events and their dependence on cloud parameters. J. Geophys. Res. 106, 15643–15656, 2001.