SEMIANNUAL BEHAVIOUR OF MONTHLY MEAN OF B_Z COMPONENT OF GEOEFFECTIVE ($K_P > 3$) CORONAL MASS EJECTIONS

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ABSTRACT

The annual/semiannual behaviour of monthly mean IMF B_z component as well as the number of hours spent by the Earth in domains of either positive or negative GSE/GSM B_y component were studied in the case of geoeffective (Kp>3) CMEs. The consecutive solar dipole cycles were separated, and definite differences were found between the annual variations of the mean values. When the solar dipole is opposite to the terrestrial one, the manifestation of the Russell-McPherron effect in the annual variation of mean GSM B_z is weak because there are strong inverse annual variations in the GSE system. However, the Russell-McPherron effect can be detected in the occurrence of the negative and positive B_y values. The case is opposite in those years when the solar and terrestrial dipoles are parallel: the Russell-McPherron effect is well detectable in the opposite annual variations of the mean GSM B_z but the occurrence of B_y directions shows polarity-independent semiannual variation.

1. INTRODUCTION

The primary cause 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 and related solar-terrestrial effect in the atmosphere: the coronal mass ejections (CMEs) and the stream-stream interaction regions formed by interaction of high speed wind streams with streams of low speed.[*Gonzalez et al.*, 1999]. The CMEs are interplanetary structures formed by plasma and magnetic fields that are expelled from the sun often associated with flares and/or erupting filaments. The decisive factors in the geoeffectiveness of CMEs are the intensity and the duration of the southward component of the IMF (B_s), i.e. the negative B_z component in the Geocentric Solar Magnetospheric (GSM) system. The B_s may be a projection of the internal field of CME ejecta or may be formed in the shock sheath caused by the interaction of CME with the surrounding interplanetary field. Intense storm can be caused if B_s>10nT during more than 3 hours while CMEs with small or highly fluctuating B_s can cause only a small or moderate storms [*Gonzalez and Tsurutani*, 1987]. The magnetic clouds are especially geoeffective CMEs. Their most impressive signature is the smooth rotation of the magnetic field direction over a large angle, which results in a long B_s interval in a part of its transit time.

The fractions of solar wind structures associated with CMEs, corotating streams and slow wind causing small, medium, large, and major geomagnetic storms depend on the solar cycle [*Richardson et al.*, 2001]. During solar minimum years the high speed streams cause most of small, medium and large storms. CMEs dominate only among the major storms. However, during solar maximum years, CMEs are dominant causes of all kinds of storms.

The large-scale structure of the heliosphere depends on the direction of the solar main dipole. When the 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 it. In this case the solar and terrestrial dipoles have opposite (antiparallel) directions. If the solar dipole reverses somewhat after the sunspot maximum, the solar and terrestrial dipoles become parallel. The leading field of magnetic clouds tend to follow that of the main dipole, and reverses at solar maximum [*Bothmer and Rust*, 1997; *Bothmer and Schwenn*, 1998; *Mulligan et al.* 1998]. Although CMEs associated with active region sigmoids show some connection with the sunspot cycle reversing at minimum [*Leamon et al.*, 2002], the dipole cycle seems to dominate the large-scale IMF structures of CMEs [*Crooker*, 2000].

It is plausible to suppose that the atmospheric effects of solar plasma streams also depend on the dipole cycle. Our earlier studies [*Baranyi et al.* 1998, and references therein] supported this hint, and revealed that the atmospheric response is sensitive to the opposite polarity circumstances of the consecutive dipole cycles, and it can distinguish between high-speed winds and CMEs. In order to be able to interpret these results it is important to study those features which exhibit a certain sensitivity to these conditions, and so could serve as intermediators between the solar and terrestrial atmospheres.

The main candidates to be actors in the above features are the IMF components. The B_z 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. The B_y component can modulate this process, causing marked asymmetries in magnetospheric convective flow patterns at high latitudes and the related ionospheric effects. Thus, the B_z and B_y components, and the durations of periods in which the Earth is exposed to an impact have to be scrutinized.

The differences between the geoeffective factors of CMEs and high-speed winds were studied in our previous paper [*Baranyi and Ludmány*, 2002]. Here we focus on the semiannual variation by studying the manifestations of the Russell-McPherron effect. We use the GSM system if we want to study how the Earth is affected, and the Geocentric Solar Equatorial (GSE) system if we want to study how the given structure appears in the heliosphere.

The transformation of the magnetic field vector from the GSE into the GSM system causes the Russell-McPherron effect [*Russell and McPherron*, 1973], which is one of the constituents of the semiannual variation of geomagnetic activity. This geometrical transformation modifies the value or direction (or both of them) 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 component depends only on the GSE B_y component. In spring a negative B_z (necessary to the geomagnetic disturbance) is projected in the GSM system by a negative GSE B_y component (toward polarity), and a positive GSM B_z is projected in the GSM system by a positive GSE B_y component(away polarity). In fall a negative GSM B_z is projected by positive GSE B_y, and positive GSM B_z is projected by negative GSE B_y. The annual variation of the GSM B_z projected by the away polarity is sinusoidal, with a negative extreme occurring shortly after the September equinox. The annual variation of the GSM B_z projected by the toward polarity has a negative extreme occurring shortly after the March equinox. If the direction of GSE B_y is that one which causes negative GSM B_z in the given season, we can say that this direction is favorable for the Russell-McPherron effect to contribute to the geoeffectiveness. 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. Thus, the absolute value of the GSM B_z depends on the actual geometrical situation. In this way the annual variation of the GSM B_z also depends on the topology of the magnetic fields of the incoming plasma streams.

Our previous study of these annual variations [*Baranyi and Ludmány*, 2003, Paper I] revealed that several characteristic features of geoeffective CMEs depend on the solar dipole cycle. In the antiparallel years the Russell-McPherron effect can not be observed in the annual variation of mean B_z measured in the GSM system. However, the opposite annual variations for the toward and away polarities can be detected in the occurrence of the geoeffective negative and positive B_y values. In the parallel years the mean GSM B_z shows the Russell-McPherron effect while the occurrence of the geoeffective hours is about the same for both directions of B_y. The present work adds further details to these results.

2. DATA SETS AND SELECTION CRITERIA

The components of IMF and *Kp* index data were obtained from the OMNI database, which is maintained and updated by NSSDC. It contains hourly averaged interplanetary plasma and magnetic field data gathered by several spacecraft, and some additional data for 1963-2002. The parallel-antiparallel subsets of years were separated after *Makarov and Makarova* [1996] and *Makarov et.al* [2000].

During the ascending phases the effects of CMEs dominate over the effects of fast wind [*Richardson et al.*, 2001]. In order to study the characteristics of CMEs depending on the dipole cycles, we use the time intervals of ascending phases. 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 (P2); 1977-80 (A2); 1987-89 (P4); 1997-99 (A4).

In these intervals we studied the annual run of the monthly means of B_z in the subsets according to the direction of B_y. We used the three-hourly *Kp* index to separate the geomagnetically active hours. We selected those hourly data when *Kp*>3, which is favorable for omitting the largest part of the effects caused by slow wind [*Richardson et al.*, 2001].

3. DEPENDENCE ON THE DIPOLE CYCLE

Here we study only those cases when the B_y has the same direction in the GSM and GSE systems. The upper panel of Figure 1 shows the annual run of the monthly mean B_z values in the GSM system by separating the periods of positive and negative B_y. One can see that during parallel years the mean B_z has stronger negative values for negative B_y in the first half of the year and for positive B_y in the second half of the year. This is a manifestation of the Russell-McPherron effect. However, this type of regularity is weak for the annual run of mean B_z in antiparallel years although one would anticipate a stronger signal during antiparallel years. We think that the reason of this feature may lay in the behaviour of the B_z in the GSE system.

The second row of Figure 1 displays monthly mean B_z values for the same events as the first row, but

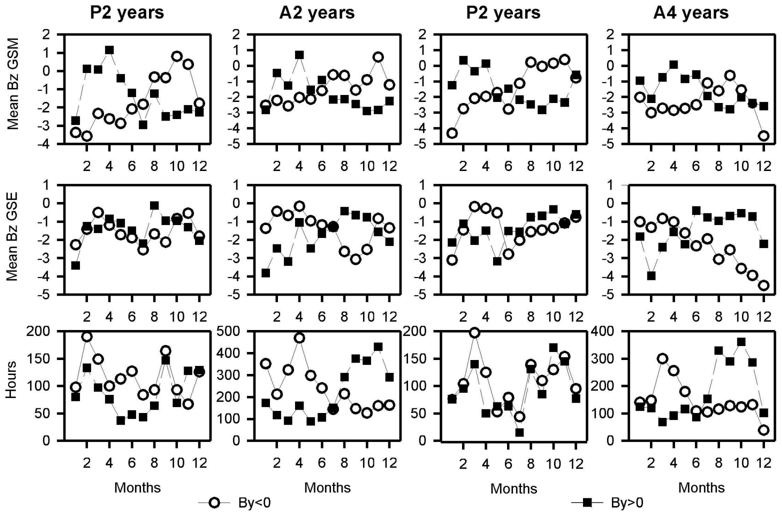

Figure 1. Annual runs of monthly mean B_z in the GSM and GSE systems, and the number of hours spent in domains of either positive or negative GSE/GSM B_y during the ascending phase of sunspot cycle if Kp>3.

expressed in GSE system. Two definite opposite annual runs of means can be seen in A2 and A4 but this pattern is missing or small in P2 and P4. In the antiparallel intervals it is remarkable that the means of B_z are much more negative for that direction of B_y which is unfavorable for the Russell-McPherron effect in the given season. This pattern may compensate the Russell-McPherron effect. In spring negative B_y (in GSE) projects negative B_z (in GSM), whereas at this time much more negative GSE B_z coincides with positive B_y, which still remains negative after the transformation into the GSM system. The case is opposite in fall. The Russell-McPherron effect is a geometrical rule, but the case of Figure 1 (second row) may hint at a topological feature of the CMEs, and these may cause two inverse patterns of mean B_z. In any case, the final result is a combination of the two effects, which may even extinguish each other. The existence of virtually inverse Russell-McPherron pattern is conceivable for the following reasons: when the direction of IMF is unfavorable for the Russell-McPherron effect, the stream can only be geoeffective if its B_z has much stronger negative values to compensate its disadvantage. Thus we can expect more negative mean B_z in the cases of unfavorable B_y than in the cases of favorable B_y. However, the separation of the curves of B_z is much larger during the antiparallel years than in the parallel years, which is absolutely unexpected and cause marked asymmetries. If the separation is small then the situation is close to the case when the magnetic field lies in the ecliptic plane. In this case the Russell-McPherron effect has a good chance to manifest itself in the annual variation of mean B_z. When the separation is large, the B_z components of unfavorable polarities have higher chance to remain negative in the GSM system in spite of the Russell-McPherron effect. At the same time the fields of favorable polarities gain enhanced negative B_z in the GSM system. Thus, the difference between the annual runs of mean GSM B_z of favorable and unfavorable polarities shows only a random character.

The third 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 antiparallel years the heliographic excursion of Earth causes that in spring the negative polarity of the southern solar hemisphere reaches Earth more often than the positive polarity of the northern hemisphere (Rosenberg-Coleman effect) [*Rosenberg and Coleman*, 1969]. As the negative B_y in spring and the positive B_y in fall projects negative B_z in the GSM system, this is a favorable condition to cause a geomagnetic disturbance. Thus, in the geomagnetically active hours the negative B_y dominates in spring and the positive B_y dominates in fall. This type of opposite annual variations of B_y occurrence cannot be seen in the parallel years. One can see polarity-independent semiannual variations instead of the polarity-dependent opposite annual variations. The explanation for this polarity-independent semiannual variation of the number of geoffective hours may come from the equinoctial mechanisms of semiannual variation (see e.g. Paper I).

These results are in agreement with that of Paper I for the ascending phases and descending phases showing that the different patterns of antiparallel and parallel cases do not depend on the fact that the direction of B_y is determined only in the GSM system or it is also the same in the GSE system. We can conclude that the existence or lack of the inverse semiannual variation of mean B_z in the GSE system depends only on the dipole cycle.

The larger separation of curves of mean GSE B_z during the antiparallel years hints that the CMEs may have much stronger negative GSE B_z values during these years. This hint is supported by Figure 2, which shows the ratio of the numbers of geoeffective cases with GSE $B_z < -5$ nT to the numbers of all the geoeffective ($Kp > 3$) cases separated according to the direction of GSM/GSE B_y. It can be seen that the fractions of the strong (<-5) GSE

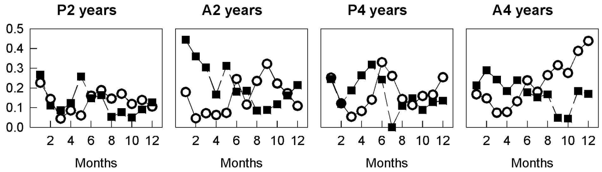

Figure 2. Annual variation of the monthly number of GSE $B_z < -5$ nT cases divided by the number of all monthly cases if $Kp > 3$. Periods of positive (square) and negative GSM/GSE B_y (circle) are separated.

B_z values separated according to the direction of B_y show definite opposite annual variations in the antiparallel years. However, the annual variations of these fractions is similar in the parallel years. This feature may refer to a substantial variation of the characteristics of CMEs depending on the dipole cycle, which may be related to the dominant polarity of the leading field of magnetic clouds [*Bothmer and Rust*, 1997; *Bothmer and Schwenn*, 1998] or to their central axial field direction [*Zhao et al.*, 2001].

4. CONCLUSION

We confirmed that several characteristic features of geoeffective CMEs depend on the solar dipole cycle. In the antiparallel years the Russell-McPherron effect can not be observed in the annual variation of mean B_z measured in the GSM system because the mean B_z of CMEs has an inverse annual variation in the GSE system. However, the opposite annual variations for the toward and away polarities can be detected in the occurrence of the geoeffective negative and positive B_y values. In the parallel years the mean GSM B_z shows the Russell-McPherron effect while the occurrence of the geoeffective hours shows polarity-independent semiannual variation.

We showed that the fraction of the strong (<-5 nT) GSE B_z values in the subset of geoeffective unfavorable polarities is larger in the antiparallel years than that in the parallel years. The fractions of the strong (<-5 nT) GSE B_z values separated according to the direction of B_y shows definite opposite annual variations in the antiparallel years. However, the manifestation of these type of opposite annual variations is weak in the parallel years. This finding may be a consequence of the dipole cycle dependent properties of CMEs, and it needs further study.

The differences between the annual runs of mean GSM B_z and in the occurrence of negative and positive GSM B_y may play an important role in 22-year modulation of terrestrial effects of CMEs.

ACKNOWLEDGMENTS

This work was supported by OTKA T037725 grant of the Hungarian Scientific Research Fund.

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