

GEOEFFECTIVE FACTORS OF SOLAR PLASMA STREAMS

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ABSTRACT

Several signatures have been reported in our previous papers indicating that solar plasma events affect some tropospheric processes. This paper focuses on the result which demonstrated that tropospheric response exhibits a dependence on the solar origin of ejected plasma (coronal mass ejections (CMEs) or high-speed wind streams). The present study is devoted to reveal the relevant factors in the underlying mechanism. The most intriguing question is as to what are the substantial differences between plasmas of different origin. Bulk speed and magnetic components of solar plasmas have been studied to reveal their role in some of our earlier published results. The present study is based on OMNI data and it is restricted to those years when the solar and terrestrial magnetic dipole fields are antiparallel. The events were separated into low, medium and high speed, and also the roles of B_y and B_z components as well as their fluctuations were considered. The paper lists the significant differences between CMEs and fast wind streams which can be responsible for the differences of their earlier detected atmospheric impacts.

INTRODUCTION

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 solar corpuscular events were described by the classified events in aa index whereas the tropospheric response was characterized by the surface temperature data of several stations on the Earth's northern hemisphere. 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 certain features and regularities in the specific responses given by the troposphere to those events in which the solar energy was carried by particles. This paper is inspired by those results which show that the tropospheric response is sensitive to the type of solar source. In the years of parallel solar and terrestrial dipole fields the aa - T correlation is positive for impacts coming from the active region belt and it is negative or vanishing for impacts from the polar regions. These roles are exchanged in antiparallel years (oppositely directed solar and terrestrial dipoles). This complex behaviour is detected in (western) Europe (Baranyi and Ludmány 1994, 1995). The opposite version of this feature is detected in the western hemisphere, the separating border lies close to the

meridian crossing the magnetic pole (Baranyi et al., 1998).

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 CMEs.

The above features reflect only a phenomenological aspect of the processes. To achieve a more profound insight, one should search similar patterns in the energy transporting medium. In other terms, in order to be able to interpret the above regularities, we should find those features of the incoming plasmas which depend on the solar (poloidal or toroidal) origin of the ejected plasma and any sort of annual/semiannual run may be relevant.

In order to find the appropriate strategy it is worth making the following considerations. Akasofu (1979) found that the total energy generated in the magnetosphere during geomagnetic storms, as well as the AE index indicating the activity level of the northern auroral zone, correlate well with a quantity $\epsilon = vB^2 \sin^4(\theta/2) l_0^2$, where v is the solar wind speed, B is the magnitude of IMF, l_0 is a length related to the section of the magnetosphere (7 Earth radii), θ is the polar angle of the IMF vector in the y - z plane of the Geocentric Solar Magnetospheric (GSM) system. (If $B_z > 0$ then $\theta = \tan^{-1}|B_y/B_z|$, and if $B_z < 0$ then $\theta = 180^\circ - \tan^{-1}|B_y/B_z|$.) The quantity vB^2 is approximately the interplanetary energy flux per unit area and $(l_0 \sin^2(\theta/2))^2$ may be considered to be the cross-section through which the energy flux flows into the magnetosphere. In this way, 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 asymmetries in magnetospheric convective flow patterns at high latitudes. As E_z , the z -component of the electric field ($E_z = vB_y$, where v is the solar wind velocity) is altered due to the reversal of the B_y component, B_y is one of the most plausible candidates to control the reported effects. Tinsley (2000) found that the linkage between the solar particles and atmospheric circulation may be the change in J_z air-Earth current density in the global electric circuit due to solar wind modulation. A basic element of

the global electric circuit is the dusk-dawn electric potential in the polar cap region. This potential is basically produced by the B_z , but the B_y also contributes to this field by varying its distribution across the polar cap. The potential variations imply variations in J_z in this region, affecting the microphysical processes in clouds.

DATA SETS AND SELECTION CRITERIA

On the basis of the above summarized results and theoretical expectations, the following quantities and properties may be scrutinized: bulk velocity, magnetic field, in particular B_z and B_y , measured in the Geocentric Solar Equatorial System (GSE) as well as their variances and the duration of intervals in which the Earth is exposed to an impact.

The components of the interplanetary magnetic fields and K_p index data were obtained from the OMNI database, which contains hourly averaged interplanetary plasma and magnetic field data gathered by several spacecraft, and some additional data. The OMNI tape is maintained and updated by the National Space Science Data Center (King and Papitashvili, 1994).

For this study we had to select the geomagnetically active hours. We used the three-hourly K_p index to separate the active and quiet hours. We selected those hourly IMF data when K_p was larger than 3 (or 30 in the OMNI format), and these are called geoeffective events in our terminology. This criterion results in a similar separation of quiet and active days as in our earlier papers where the criterion for active days was $aa > 19$.

The parallel-antiparallel subgroups of years were separated by the solar dipole field polarity after Makarov and Sivaraman (1986) as in the previous papers. This work focuses on the antiparallel years: 1972-80, and the study of differences between the antiparallel and parallel dipole cycles will be studied in another paper (Baranyi and Ludmány, 2002).

IMF COMPONENTS AND BULK SPEED

It follows from Akasofu's expression that the same activity level can be generated by a slow stream which brings strong magnetic field or a high speed wind stream with a relatively weak magnetic field. The relative roles of these two factors in the different kinds of solar streams can be studied by separating into three domains of bulk velocity: the slow ($v \leq 420$ km/s), moderate ($420 < v \leq 540$ km/s), and high speed ($v > 540$ km/s) domain. A further criterion is the above mentioned $K_p > 3$ threshold to separate the quiet and disturbed hours. We can estimate the dominant type of streams in the velocity domains from the fact that the average velocity of CMEs at 1 AU is about 450 km/s (Richardson et al. 2002). One substantial part of the CMEs is in the velocity range of the slow wind, but the slow wind streams are rarely geoeffective, so the CMEs are the dominant causes of geomagnetic activity in this

range. Most of the CMEs is in the middle velocity domain. However, the forward part of a 'slow stream' - 'fast stream' interaction region is also in this domain. Consequently, this domain is a mixture of the different types of streams. The high-speed domain is dominated by coronal wind streams. There are also CMEs in this velocity range, but their rate is small compared to the wind streams.

Figure 1 shows the monthly means of the negative B_z component and the absolute values of B_y component as well as their variances under different circumstances measured in the GSE system. We only considered the negative B_z values, which play an important role in the geoeffectiveness. All parameters under study were plotted in monthly separation to reveal any semiannual variation.

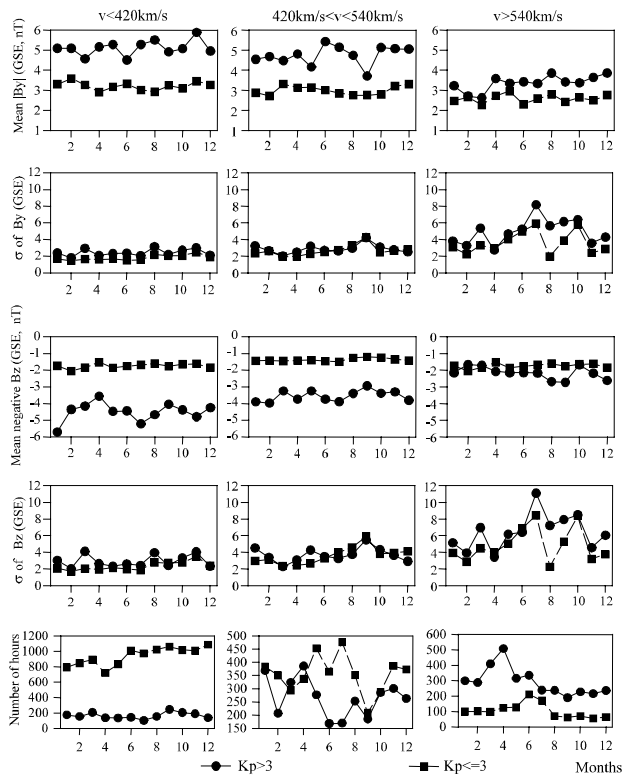


Fig. 1. Annual behaviour of monthly means of B_y and negative B_z as well as their σ values for three groups of velocities with distinction of quiet and disturbed states, and the number of hours.

The first row of Figure 1 shows the behaviour of B_y depending on the bulk speed. Its average for quiet hours ($K_p \leq 3$) depends only slightly on the bulk speed, but the averages of B_y for disturbed hours ($K_p > 3$) exhibit strong dependence on the speed. The difference between the means of quiet and active hours decreases with increasing speed. The similar is true for the mean values of B_z for the selected cases of $B_z < 0$. The means of negative B_z have about the same value at any speed in quiet hours but in disturbed hours they decrease with increasing speed (third row). If the speed is moderate (middle column), weaker negative B_z values are

sufficient to result in $K_p > 3$ states, than in the range of the slow wind. If the high speed wind stream reaches the Earth (third column), there is no substantial difference between the mean B_z values of quiet and disturbed hours. For high speed wind streams the averages are practically equal in the cases of $K_p > 3$ and $K_p \leq 3$. The low speed case also contains an interesting feature: a specific appearance of the semiannual effect, i.e. at equinoxes weaker negative B_z values are enough to produce disturbances.

The variances of B_z and B_y (second and fourth rows) increase with the bulk velocity. The causes of this speed-dependent variance are the fluctuations of the compressed and intensified fields of the slower wind and the large amplitude Alfvén waves accompanying the high-speed streams (Tsurutani et al. 1994). The K_p index is measured in three-hour intervals and any quick and high fluctuations of the direction of B_z can result in zero mean, although the short-time intervals of large negative B_z cause large geomagnetic activity. The variance also modifies the duration of the energy transport, which may also be decisive for the geoeffectiveness of a particle stream. In the case of CMEs the variance is low and it is not rare that the interval of negative B_z is longer than 15 hours. In the case of wind streams the intervals of negative average B_z are shorter, but even in these intervals the reconnection and the energy injection is intermittent because of the high variance of the IMF in the fast wind.

The fifth row demonstrates that in the case of slow winds we usually have geomagnetically quiet hours but if we have strong negative B_z (probably caused by a CME) then it results in disturbed hours. In the case of high speed streams the K_p is usually high. The number of hours of $K_p > 3$ is about twice as high as that of $K_p \leq 3$ for these streams.

DISCUSSION

Gonzalez et al. (1999, and references therein) point out that the decisive factors in the geoeffectiveness of CMEs are the intensity and the duration of the southward component of the IMF (B_s). An intense storm can be caused if $B_s > 10$ nT during more than 3 hours in the GSM system. If the CME does not have a substantial B_s or the B_s is highly fluctuating, the CME can cause only a small or moderate storm. The intensity of the B_s depends on the velocity of the CME if it is a magnetic cloud, but it does not if it is a non-cloud event. Thus, one can only expect a weak connection between the speed of CMEs and their geoeffectiveness on an average. This was confirmed by Cane et al. (2000). They found that there is a strong correlation between the D_{st} index and the strength of IMF southward component in the CME events. However, the connection between the size of a storm (D_{st}) and the transit speed of the CME is weak.

Gonzalez et al. (1999) also found that the corotating streams are less geoeffective than CMEs. The main

factor of their impact is the highly fluctuating B_z component, which causes intermittent reconnection, intermittent substorm activity (large AE), and sporadic injections of plasma sheet energy into the outer portion of the ring current. This causes small but prolonged decay of D_{st} and High Intensity Long Duration Continuous AE Activity (HILDCAA) events. This hints that in this case the incoming energy is dissipated mainly by the auroral electrojet. Since the fluctuation increases with the increase of the speed, the geoeffectiveness of the wind depends on the velocity. Some additional energy may be absorbed through viscous interaction (Kelvin-Helmholz instability or magnetosheath cross-field diffusion due to magnetopause boundary waves), although the efficiency of this interaction is estimated to be only about 1%.

Similar differences between effects of CMEs and wind streams were found by Huttunen et al. (2002a, 2002b). They found differences between the behaviour of the K_p index (which has significant contributions from high-latitude auroral electrojets) and D_{st} index (which has a dominant contribution from the equatorial ring current). The storms caused by interaction regions or fast wind streams usually reach only a weak or moderate D_{st} value, but they are more likely to show larger activity according to the K_p index. The K_p index seems to respond strongly to short-time and intense negative B_z events, which are also typical for post-shock streams and sheath regions of CMEs. This may explain that, although strong correlation was found between D_{st} and K_p indices in the cases of CME-related events, there are differences between them. If the storm is associated with a shock or sheath region of the CME, the K_p index is likely to indicate a stronger storm. If the shock is followed by an ejecta, the D_{st} index is likely to indicate a stronger storm. In the latter case the peak of the D_{st} index is usually not reached before the ejecta arrives in the magnetosphere. At the same time K_p usually maintains its value achieved during the passage of sheath region or even starts decreasing.

Our results are in good agreement with the above results. On the basis of these findings, we can conclude that in the case of high-speed wind streams the large variance plays a decisive role in the generation of geomagnetic activity and atmospheric response, while in the case of CMEs the strong and long duration of negative B_z dominates. In the latter case those processes may be relevant, which are weak or absent in the case of high-speed streams. According to Akasofu (1979) the total dissipated energy U includes the ring current energy, joule heat energy associated with the auroral electrojet and the kinetic energy deposited in the polar ionosphere by auroral particles. It seems to be plausible that the way in which the total energy is divided into these energies depends on whether the high fluctuation of the IMF or the stable negative B_z is predominant.

Although both types of streams affect the polar region, their effects are also different even in this region (Legrand and Simon, 1989). The spread of aurorae in latitude is smaller in the cases of high speed winds than

in the cases of CMEs. The auroral effects of high speed streams are confined to higher latitudes than the effects of mass ejections. They concluded that the flux of particles precipitated into the ionosphere is larger in the case of a shock than in the case of a wind stream, and this precipitation might take place at lower invariant latitude than in the case of wind stream activity.

CONCLUSION

CMEs affect the Earth mainly by their large B_z and B_y IMF components. The durations of negative B_z is long (3-21 hours), so there are long intervals when enhanced energy and particle transport is possible. The atmospheric response to the CMEs may primarily be governed by those mechanisms which prefer stable B_z and B_y directions persisting for several hours, or they may be mainly associated with the energy dissipation from the ring current. Furthermore, the particles, which can penetrate to medium latitudes, can play an important role in the atmospheric processes.

The fast wind streams affect the Earth mainly by their highly fluctuating magnetic field. Their effect is more or less confined to the polar region and the incoming energy is dissipated mainly by the auroral electrojet. Thus, only those atmospheric processes can be affected by the wind which can respond quickly to these high fluctuations of magnetic fields or which are in connection with the auroral electrojet. The high speed may enhance the role of the viscous effect, although the efficiency of this interaction is low.

The above reported features may help to reveal the factors contributing to the results which show that the CMEs and the fast wind streams can affect the lower atmosphere in different ways and in different latitudinal distributions. The specific mechanisms of the atmospheric response need further investigation.

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