Magnetic storm cessation during sustained northward IMF

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Abstract

Times of sustained strong northward IMF can interrupt the magnetic storm development and lead to lower levels of geomagnetic activity for many hours. During 1997–2000 we have found two events of this kind observed on November 8, 1998 and October 13, 2000. In both cases, the storms started as usual after arrival of ejecta with a southward IMF component from the Sun to the Earth, but ceased after several hours due to the onset of sustained northward IMF leading to the faster recovery process. After the passage of this so-called positive domain, the storm development started again. The heliospheric magnetic field intensity remained enhanced and nearly constant. The solar origins of the geomagnetic storm interruptions have been investigated. Tentatively they may be related to strong nonlinear Alfvén type solitary waves excited by non-stationary coronal current variations with a characteristic time-scale of about a day.

Keywords: Magnetic storm cessation; Northward IMF; Interplanetary magnetic field; Space weather

1. Introduction

The necessary and sufficient heliospheric conditions for the geomagnetic storm development are now well known. They are mostly of electromagnetic origin and usually expressed as “sufficiently large and sustainable southward interplanetary magnetic fields” or “strong negative Bz, for several or many hours” (see e.g. Tsurutani, 2001). We have checked this rule using our database (www.decl.sinp.msu.ru/apev) for all significant geomagnetic perturbations during the current solar cycle in 1997–2001 (Bothmer et al., 2002). Solar origins of these heliospheric perturbations are still under investigation. Different markers, signatures or indicators of sporadic geo effective solar events are associated with coronal ejections, magnetic flux ropes having strong fields and proper orientations. Long-lived coronal holes are assumed to be sources of fast solar wind streams and strong Alfvén waves leading to recurrent geomagnetic storms, which are weaker than sporadic storms could be. Many examples of sporadic, recurrent and combined perturbations can be found in the mentioned database base which contains solar wind and heliospheric magnetic field parameters measured on board satellites and available information about the solar structures and processes seen in the corona, chromosphere and photosphere during significantly perturbed conditions. In spite of many efforts, solar origins of geomagnetic

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storms are still elusive in many instances and we cannot indicate necessary and sufficient conditions on the Sun leading to the geomagnetic storm development with given amplitude in a given time. The problem is too complicated.

We studied the list of more than 250 significant geomagnetic perturbations during 1997–2001 and have identified isolated and overlapping perturbations from one or several solar sources acting simultaneously or separately in time (Bothmer et al., 2002). The purpose of this paper is to present two specific examples from this list showing the magnetic storm cessation by interplanetary conditions. Selected events in November 1998 and October 2000 are not so common, but they are interesting from the point of view of a better understanding of the related physical processes. In these cases, the magnetic storms started to develop, but where interrupted for several hours or a day due to the northward interplanetary magnetic field turn during this period. The development of the storms continued when the interplanetary magnetic field turned again to the southward orientation.

2. Perturbed period of November 7–14, 1998

This period corresponds to events 58–62 in our list of significantly perturbed days (http://alpha.sinp.msu.ru/apev). Fig. 1 shows the heliospheric parameters and the geomagnetic indices during the storm, which started with the sudden commencement after the weak shock wave arrival on November 7. The main phase of the storm clearly consists of three magnetic bays, which lasted on November 7, 8, 9 correspondingly. The bays are marked by numbers 1, 2, 3 at the top panel in Fig. 1.

Fig. 2 illustrates the complicated situation on the Sun with several disappearing filaments, flaring phenomena, changing coronal holes, the heliospheric current sheet passage, etc. in the region near the central meridian, which is known to be the most geo effective area from many previous statistical studies.

It is interesting to note, that bays developed (and ceased) after the arrival of the domains with strong southward (northward) interplanetary magnetic fields. The second rather strong shock wave on November 8 with the positive magnetic field behind it clearly interrupted the further magnetic storm development and lead to the fast recovery during the remaining part of this day. The new development and the third bay are associated with the arrival of the strong negative interplanetary magnetic field and not with other heliospheric parameters. We can mark the very rapid recovery for bay number two with the characteristic exponential time of several hours instead of the statistically average values \( \tau \sim 14 \pm 4 \) h (Dasso et al., 2002). The magnetic field intensity \( B \) (dotted line in Fig. 1) is rather big and decreases only slowly from more than 30 to 10 nT during the most interesting period on November 8–9. The changes in the orientation of the field are not accompanied by changes in its intensity, which is indicative of the Alfvénic character of the perturbation.

3. Perturbed period of October 13–14, 2000

This period corresponds to events 194–195 in the list of events (http://alpha.sinp.msu.ru/apev). Figs. 3 and 4 show the heliospheric and solar situation before and during the period of this moderate geomagnetic perturbation. Some common and specific features can be seen when comparing this case with the events of November 7–14, 1998 discussed above. The nonlinear Alfvén wave train arrived with other convective and compressive perturbations in the solar wind plasma and magnetic field behind the shock wave front on October 12. Also, the sustained northward turn of the interplanetary magnetic field stopped the development of the magnetic storm for several hours on October 13. The new development started again after the magnetic field rotation to the south. Again, the partial recovery phases are unusually fast, only several hours.

The solar situation is also rather complicated with multiple solar perturbations and eruptions. They all can be considered only as signatures, but not “causes” of perturbations. The real physical drivers of solar, heliospheric and geomagnetic perturbations – strong electric currents – remain invisible. We observe only their manifestations in magnetic fields, plasma motions and dissipative processes in the solar atmosphere, heliosphere and magnetosphere. This statement is supported also by the available spacecraft and satellite images, magnetograms and movies obtained onboard SOHO, TRACE and YOHKOH (see e.g. http://www.lmsal.com/SXT/movies/sxt.wmmovie_02040203382x.html, also
040429x.html) showing ample diversity of interrelated active processes on the Sun during this period at all levels of the solar atmosphere.

4. Interpretation

The interpretation of the observed cessation of geomagnetic storms and their new development can be associated with the strong heliospheric electric currents manifested by their positive and negative fields influencing the storm development and the cessation. The Earthward direction of the magnetospheric convection in the tail is enhanced only during the southward interplanetary magnetic field and leads here to the formation of the partial ring current. The magnetic storm development “switches on” in this case and “switches off” in the opposite case. In addition to this, heliospheric electric currents partially penetrate into the magnetosphere and enhance the storm when coincide with the direction of the currents inside the current sheet in the geomagnetic tail. This happens only in the case of the positive-negative interplanetary magnetic field transition. This second effect is rather small and we confirm the known conclusion about the main role of the southward magnetic field. In the well developed empirical multiparametric analysis starting with idea that the toroidal ring current determines the magnetic effects of the geomagnetic storm, the physical concept is incorporated that the ring current injection is completely governed by the interplanetary electric field, when the decay is determined by the charge-exchange of ions on the neutral atmosphere atoms (O’Brien and McPherron, 2000). The injection term is assumed to be efficient only during the negative $B_z$ and switched off during the positive $B_z$. The decay exponent also depends on the external electric field, probably because of the deeper injection of the ring current in the denser neutral atmosphere by stronger negative $B_z$. These authors presented two examples of the storms with the monotonous development and recovery phases lasting for several days. Our cases differ in this respect. They have much more shorter individual recovery phases. We can assume that the toroidal ring current of trapped ions was not completely formed. The contribution of the drifting not-trapped population in the partial ring current was significant and controlled by the external electric fields. With the
turn of the magnetic field to the north, plasma particles went away from the Earth to the tail and their magnetic effect on the ground rapidly decreased with the characteristic time of the tailward convection, not the charge-exchange losses. This preliminary interpretation needs deeper analysis of the storm cessation events, which are clearly associated with the interplanetary magnetic fields and controlled by them.

We mark that the intensity of the interplanetary magnetic field in both studied cases was strong and nearly constant during the cessation (development) and only the direction of the interplanetary magnetic fields and currents changed drastically which confirms our interpretation. The heliospheric situation can be described as a manifestation of strong nonlinear Alfvén wave in a shape of a soliton or a wave train propagating in the inhomogeneous medium. The wave was launched by non-stationary coronal current variations with a characteristic time scale of about a day and propagated in the expanding solar wind. The alternative (more standard) interpretation could be expressed in terms of multiple flux ropes moving with the solar wind. The remarkable property of such flux ropes in our case is that they are tightly neighboring each other and clearly demonstrate the rotational character of the field. The flux rope system is in the state of the approximate magnetic pressure balance. We stress that both interpretations are admissible and equivalent in our case. It is because of the nearly constant magnetic field intensity with no strong compressions or rarefaction during the magnetic storm cessation events. It is well known that propagating Alfvénic discontinuities and convective tangential ones do not differ and coincide in the case when the normal component of the field is zero. The propagation speed for the Alfvénic structure in the plasma reference frame is equal to zero in this case. Finally, the language of field aligned electric currents is also appropriate for the interpretation of our observations. Hence, the multiple system consisting of several wave trains, flux ropes or electric currents exists and leads to the repeated initiation and cessation of magnetic storms in the considered cases. No matter how we term these interplanetary magnetic structures, but they are generated near the Sun due to the time variable electric currents, also convective or wave-like ones. The distinct difference between them can be established only for small MHD perturbations. For nonlinear perturbations such classification does not exist as a rule and cannot obscure the physics.

The analysis of two events confirms the result gained from the study of the whole list of more than 250 significant geomagnetic perturbations: all big events in the magnetosphere are directly driven by strong heliospheric currents and magnetic fields associated with them. Big storms are not related principally to the spontaneous instabilities in the stored free energy reservoirs inside the magnetosphere. Naturally, other heliospheric parameters also play their role in the development and the intensity of geomagnetic storms. For example, the ram pressure of the solar wind is the main controlling factor of the overall size of the magnetosphere, but this dependence generally follows the very slow power law with the index about 1/6 only. All current systems are situated closer to the Earth and produce stronger effect on the ground for the highly compressed magnetosphere in the fast dense solar wind streams. Nevertheless, the interplanetary magnetic field controls the magnetic storm development much more efficiently and directly than other interplanetary parameters. This fact is well known.

During the initial phase of the magnetic storm development the magnetosphere is essentially open for external magnetic fields and electric current penetration. Storm-related electric currents are generated and closed mainly inside the magnetosphere. External heliospheric currents concentrate also in the tail region with its higher electrical conductivity because of the existence of the hotter and denser plasma sheet here. The magnetic configuration is more closed during the northward interplanetary magnetic field orientation. Under this condition, external heliospheric magnetic fields and currents do not penetrate deep inside the magnetosphere. This picture is consistent with observations of the storm cessation.

5. Discussion

Solar origins of geomagnetic perturbations are often difficult to localize especially for weak and moderate events which are rather frequent, but not so high above the continuous noise level. Such events can easily overlap in time for different regions on the Sun and in space when propagating from the Sun with different velocities in the heliosphere. Multiple interacting perturbations are not so rare. The storms development in two or more steps is statistically observed in about 20% of cases (Vieira et al., 2001). When they have comparable amplitudes, we observe non-monotonous development of magnetic storms with two or more onsets during half a day or so. In the examples analyzed in this paper we see two and three onsets. Multiple events are interesting mainly because of their capability in producing accelerated particles due to the possibility of the Fermi acceleration of energetic particles between converging magnetic mirrors in the heliosphere. Strong multiple perturbations appear during the high activity in one or several regions on the Sun. Old attempts to find the localized or point-like “primary energy release sites” failed in many cases namely because of misunderstandings with the space-time scales involved in this essentially non-local process of the initiation. Now we understand that magnetically coupled morphological elements on the Sun are
involved simultaneously, and not only solar flares as the brightest dynamical manifestation, sunspots with strongest fields and active regions seen on the photospheric level, but also related chromospheric and coronal features taken together in large areas and volumes.

Eruptive events associated with some active or disappearing filaments, prominences, evolving coronal cavities, channels and holes are regularly registered by optical and radio observations in different wave lengths indicating that all visible heights in the solar atmosphere could be involved in the process. Ejecta are essentially non-local phenomena with many coupled space-time scales demonstrating the complicated geometry and time evolution. Because of this, the real modeling is very difficult and we cannot calculate or predict with a sufficient precision the most essential parameters of possible or developing ejecta starting with available solar observations and theoretical schemes.

The complicated internal structure of geo-effective solar wind streams was anticipated long ago based on the studies of geomagnetic storms with two or more active periods (Afanasieva, 1961; Afanasieva et al., 1962; Ballif et al., 1969). The role of force-free flux ropes was assumed (Afanasieva et al., 1962), but the proper understanding was not possible because of the lack of sufficient information about solar and heliospheric parameters. The magnetospheric situations under the northward interplanetary magnetic field are modeled numerically when neglecting the heliospheric current penetration into the magnetosphere as an imposed boundary condition (Song et al., 1999). It is interesting to have numerical runs allowing such a penetration.

6. Conclusions

We have presented two examples of the magnetic storm development interrupted during sustained northward IMF. The suggested interpretation is associated with strong nonlinear Alfvén waves excited by non-stationary coronal current variations with characteristic times of about a day and propagating in the heliosphere. We assume that the observed magnetic storm cessation during several hours happens not only because of the charge-exchange losses of the ring current, but also enhanced by the particle drifts which evacuate the current currying plasma in the night side of the magnetosphere to the greater distances from the Earth due to the northward interplanetary magnetic fields.

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