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Study of the solar wind streams associated with intense geomagnetic storms

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Abstract. A set of 50 intense geomagnetic storms follows the criteria of $D_{st}\leq-100$ nT, IMF $B\geq10$ nT with time duration ≥ 3 hr., during the solar maximum period (1989-91) of solar cycle 22 have been analysed. The study of this short period 1989-91 has a unique importance because the maximum phase of solar cycle 22 containing large time duration 3 yr and two solar peaks, during the year 1989 and 1991 are exceptional among other previous 21 solar cycles. Recent work demonstrated some important characteristics and different solar and interplanetary associations of 50 selected storm events, which are mentioned in Table 1. Out of 50 storm events, it is found that maximum numbers of intense geomagnetic storms are associated with transient disturbances in solar wind streams, which causes strong interplanetary shocks in interplanetary medium, whereas, a few numbers of intense geomagnetic storms are associated with corotating flows in solar wind streams. We have described two intense geomagnetic storm events associated with corotating flows and transient disturbances respectively and concluded that kind of solar wind does not effect the general characteristics and variation trends of different phases of storms. The association of supersonic shocks and magnetic clouds with intense geomagnetic storms have also been discussed.

Key Words : coronal mass ejections, coronal holes, interplanetary shocks, supersonic shocks and magnetic clouds.

1. Introduction

Geomagnetic storms are large disturbances in the geomagnetosphere, often persisting for several days or more. During geomagnetic storms, the magnetic field measured at the earth's surface is perturbed by strong electric currents flowing within both the magnetosphere and the ionosphere, the aurora brightens and extends to low magnetic latitudes, and intense fluxes of energetic charged particles are generated within the magnetosphere. It is defined as periods of strengthened ring current in the magnetosphere, and correlate remarkably well with the southward excursion of interplanetary magnetic field (Burton et al., 1975). In general geomagnetic storms are attributed to two heliospheric features – recurrent stream interaction regions and transient disturbances. The recurrent stream interaction regions or corotating flows are magnetically open, long-lasting, high speed flows in quiescent solar wind, usually originating in coronal holes (CHs) and exhibiting an apparent tendency to recur with the 27 day rotation period of the Sun. Bartels (1934) postulated the so-called solar M-region as the source of these recurrent disturbances. Now it is widely accepted that coronal holes are sources of high-speed solar wind streams. Nolte et al., (1976) have shown that coronal holes coincide with high velocity streams in the solar wind and they produce recurrent geomagnetic disturbances. The second rather transient disturbances arise from the transient eruption of close-field solar regions and are mostly associated with coronal mass ejections (CMEs). Currently, it is believed that the CMEs can be produced by restructuring of the corona, and can significantly perturb the solar wind and disrupt the earth's environment (Webb 1995, Webb et al., 1994). Ulysses recent journey over the poles of the Sun has provided new insights of the three-dimensional nature of both types of solar wind flows and their evolution with heliocentric distance and latitude.

Solar rotation causes two pairs, namely, fast and slow solar winds, per solar rotation along a radial line fixed in space. The fast and slow solar winds arising from the northern and southern hemispheres of the solar disk interact with one another at low latitude, producing compressive structures in interplanetary space and causing the forward-reverse shock pairs in the solar wind streams (Hundhausen and Gosling 1976, Smith and Wolfe 1976). The forward shocks propagate into the slow plasma ahead while the reverse shocks propagate back into the high-speed streams. Both shocks are convicted away from the Sun and exhibit supersonic flow in the solar wind stream. Recently, it is believed that two kinds of interplanetary shocks termed as magnetic clouds and supersonic shocks are most effective for solar-terrestrial disturbances. First is magnetic clouds (or flux rope) as discussed by Burlaga et al. (1990). Second is plasmoid or bubble is preceded by a shock wave that bends the IMF, so that it becomes draped as proposed by McComas and Gosling (1988). Kahler and Reames (1991) proposed that a shock may be associated with a twisted, tangled IMF that the footpoints embedded and the sun and the other ends out in the distance heliosphere. Generally the interaction of lower solar wind with high-speed streams produces supersonic shock waves, but magnetic clouds are formed at the time when solar wind contains relatively strong magnetic fields, the smooth magnetic field vector is higher than average, and a low proton beta and proton temperature (Burlaga et al. 1981). The magnetic field configuration in magnetic cloud is approximately force-free (Goldstein 1983). Considering previous work associated with geomagnetic disturbances with solar wind streams and interplanetary shocks, our aim here is to examine this association applied on maximum phase of typical solar cycle 22, containing large time duration and two solar peaks.

2. Data set and analysis

In this work, we have sorted out intense geomagnetic storms which follows the criteria of $D_{st} \leq -100$ nT, IMF B≥10 nT with time duration greater than 3 hrs., during the solar maximum period (1989-91) of solar cycle 22. The hourly values of geomagnetic index D_{st} has been obtained from Solar Geophysical Data (SGD) bulletins. The different solar wind streams and interplanetary magnetic field data measured through a number of spacecraft's/satellites have been compiled and reported for different periods by (King, 1994). The selected 50 intense geomagnetic storm events, their important characteristics and association with two kinds of solar wind streams and different interplanetary parameters are listed in Table 1. In this Table the first and second columns contain the serial number and the date of the observed geomagnetic storms. The third column presents the peak magnitude of storm in nT. The different interplanetary parameters such as peak velocity of solar wind streams, peak IMF B, peak value of southward directed IMF B_z, Types of interplanetary disturbances (IPDs) and associative kinds of solar wind streams are denoted in column's 4-8 respectively. There are some data gaps in the interplanetary medium data book, so we introduce the symbol '*' for the data gap in the Table 1.

Table 1. Intense geomagnetic storms, their associative interplanetary parameters, and association with two kinds of interplanetary disturbances and solar wind streams.

S. No	Date of observed Storms	Peak Magnitude (nT)	Maximum S W V kms^{-1}	Peak IMF B (nT)	Peak IMF B_z (nT)	Type of Interplanetary disturbalances	Type of Solar Wind Streams
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
01	11-01-89	−132	744	25.9	−12.7	IP Shocks	Corotating flows
02	16-01-89	−122	685	13.9	−09.1	IP Shocks	Transient disturbances
03	20-01-89	−122	*	*	*	*	*
04	09-03-89	−103	551	17.6	−08.8	IP Shocks	Transient disturbances
05	14-03-89	−599	>839	>22.7	>−5.0	IP Shocks	*
06	16-03-89	−118	43	22.7	−08.1	IP Shocks	Transient disturbances
07	19-03-89	−110	880	22.7	−07.6	IP Shocks	Corotating flows
08	29-03-89	−131	750	15.4	−09.8	IP Shocks	Transient disturbances
09	14-04-89	−105	458	15.1	−11.5	IP Shocks	Transient disturbances
10	26-04-89	−132	646	22.5	−15.3	IP Shocks	Corotating flows
11	10-06-89	−144	>523	*	*	*	*
12	15-08-89	−146	667	32.7	−25.3	IP Shocks	Transient disturbances
13	29-08-89	−153	456	21.1	−16.3	M. Cloud	Transient disturbances
14	16-09-89	−125	*	*	*	*	*
15	19-09-89	−257	>489	>8.6	>−5.0	IP Shocks	*
16	26-09-89	−157	>374	*	*	*	*
17	21-10-89	−270	918	33.5	−19.7	IP Shocks	Corotating flows
18	13-10-89	−124	497	15.0	−12.8	IP Shocks	Transient disturbances
19	17-11-89	−266	>347	>10.9	>−2.6	IP Shocks	*
20	31-12-89	−104	672	18.4	−14.2	IP Shocks	Transient disturbances
21	12-03-90	−159	*	*	*	*	*
22	21-03-90	−133	623	17.8	−12.5	IP Shocks	Transient disturbances
23	25-03-90	−116	*	*	*	*	*
24	30-03-90	−182	616	17.9	−05.5	IP Shocks	Transient disturbances
25	10-04-90	−278	>491	>10.0	>−8.6	IP Shocks	Transient disturbances
26	12-04-90	−172	757	33.1	−19.6	IP Shocks	Corotating flows
27	17-04-90	−112	*	*	*	*	*
28	24-04-90	−107	521	>9.1	−05.1	IP Shocks	Transient disturbances
29	29-04-90	−101	*	*	*	*	*
30	13-06-90	−152	778	31.9	−14.6	IP Shocks	Corotating flows
31	29-07-90	−129	*	*	*	*	*

Table 1. continued

S. No	Date of observed Storms	Peak Magnitude (nT)	Maximum S W V kms^{-1}	Peak IMF B (nT)	Peak IMF B_z (nT)	Type of Interplanetary disturbances	Type of Solar Wind Streams
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
32	26-08-90	−116	777	22.6	−12.6	IP Shocks	Transient disturbances
33	10-10-90	−133	>493	>12.6	−11.9	IP Shocks	Transient disturbances
34	27-11-90	−136	579	20.9	−16.7	IP Shocks	Transient disturbances
35	25-03-91	−298	>414	>21.5	>−14.2	IP Shocks	*
36	17-05-91	−103	*	*	*	*	*
37	15-06-91	−219	710	*	*	*	*
38	10-06-91	−131	*	*	*	*	*
39	11-06-91	−138	*	*	*	*	*
40	13-06-91	−108	850	*	*	*	*
41	09-07-91	−198	747	32.5	−24.5	M. Cloud	Transient disturbances
42	13-07-91	−185	>588	*	*	*	Transient disturbances
43	02-08-91	−113	711	22.9	−16.5	M. Cloud	Transient disturbances
44	19-08-91	−170	725	24.8	−18.4	M. Cloud	Transient disturbances
45	30-08-91	−111	560	22.6	−15.3	IP Shocks	Transient disturbances
46	02-01-91	−162	>513	*	*	*	*
47	29-10-91	−251	994	41.6	−10.7	IP Shocks	Corotating flows
48	09-11-91	−354	>500	>12.8	−04.8	IP Shocks	Transient disturbances
49	19-11-91	−123	*	*	*	*	*
50	22-11-91	−137	771	18.7	−11.5	IP Shocks	Transient disturbances

3. Results and discussion

From Table 1, no significant correlation has been found between two kinds of solar wind streams and magnitude of intense geomagnetic storms. This result indicates that both kinds of solar wind streams are able to produce intense geomagnetic storms. Actually, the magnitude of storms is strongly correlated with electromagnetic coupling, **VxB**, of solar wind speed and interplanetary magnetic field IMF B on the geomagnetosphere. The southward directed IMFs provide an opportunity to enter the solar plasma field in the geomagnetosphere. When the IMF has large magnitude (≥10 nT) and a large southward component, the amount of transferred energy becomes very large. On the other hand, the transferred energy becomes very small when the IMF is directed preliminary northward. The energy transfer efficiency is of the order of 10% during intense magnetic storms as discussed by Gonzalez et al. 1989. Viscous interaction, the other prime energy transfer mechanism proposed, has been shown to be only < 1% efficient during intense northward directed IMFs. Tsurutani et al. (1992b) have examined the interplanetary and solar cause of five largest geomagnetic storms during the period 1971-86 and found that the extreme value of the southward IMF B_z, rather than the solar wind speeds, are the primary causes of great magnetic storms. So, the presence of large southward IMF B_z during higher solar wind velocities can produce large magnitude of geomagnetic storms, it can extend the different phase of the storm and *vice verse*.

The intense geomagnetic disturbances are caused by both kinds of solar wind flows. During our study period, out of 50 intense storms 22 are associated with transient disturbances, 07 storms are associated with corotating flows and we have not analysed 21 events due to data gaps in IMP data book. These results and symmetry trend show that the maximum numbers of intense geomagnetic storms are caused by transient disturbances in solar wind streams during the maximum phase of solar activity. Coronal mass ejections are now considered by many authors as the solar origin of interplanetary disturbances and transient disturbances in solar wind that causes large non-recurrent geomagnetic storms, while, corotating flows are associated with long-lived solar coronal holes and generally able to produce recurrent geomagnetic disturbances. In our previous work, we have shown a good association of different types of large geomagnetic storms with CMEs for maximum and minimum phases of solar cycle 22 (Dubey 1998; Dubey 2000; Dubey and Mishra 2000) and concluded maximum numbers of intense geomagnetic storms are caused by CMEs during aforesaid period. The transient disturbances are associated with CMEs, so, here we find that the maximum numbers of intense geomagnetic storms are associated with transient disturbances and only a few numbers of intense geomagnetic storms are associated with corotating flows in solar wind streams.

The corotating flows and transient disturbances associated with geomagnetic storms are either caused by supersonic shocks or magnetic clouds. In our study period, out of 50 storms, 29 storms are associated with supersonic shocks, 04 are associated with magnetic clouds and we have not analysed 17 events due to data gaps in the IMP data book. These associations and symmetry trend show the majority of geomagnetic storms were associated with interplanetary disturbances caused by flow of supersonic shocks in comparison to magnetic clouds associated with geomagnetic storms, whereas magnetic clouds associated with geomagnetic storms containing higher IMF B magnitude for longer duration in comparison to other supersonic shocks associated geomagnetic storms. The negative polarity of IMF increases the magnitude of geomagnetic storms as discussed in our previous work (Dubey and Mishra 2000). It also seems that the magnetic clouds associated geomagnetic storms could not contain higher magnitude. These results indicate that the presence of higher IMF B for longer duration is not necessarily more effective for producing large magnitude geomagnetic storms.

The solar cycle 22 is exceptional among other previous 21 solar cycles, because it contains large time duration 03 yrs. and two solar peaks. Generally, solar cycles having one peak during the solar maximum year. Solar cycle 22 peaks at first during the year 1989, then gradually decreases and peaks during the year 1991. Actually the cause of two solar peaks is associated with the internal processes of the sun, but during the complete solar maximum period 1989-91, the behaviour of solar activity is like other solar cycles as discussed by various authors and literature. So the time factor of solar cycle is not associated with the different phase of solar activity cycles.

The intense geomagnetic storms are either associated with transient disturbances or corotating flows having the same properties. For better understanding of this result and different characteristics of intense storm events, we have analyzed two intense storm events observed during 25/4/89 – 1/5/89 and 8/7/91 – 12/7/91. The onset of initial, main and recovery phases are indicated by vertical lines in both figures. The first storm event observed on 25/4/89,

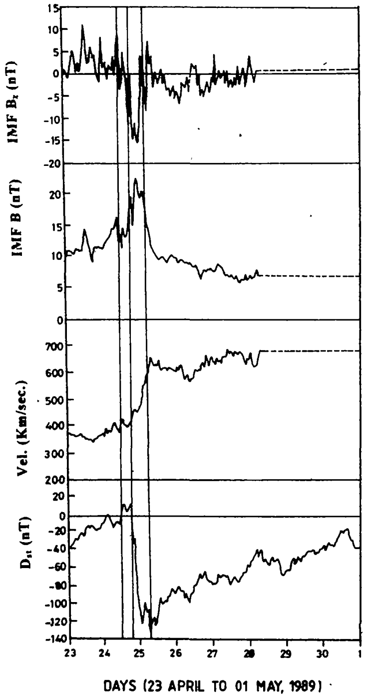

Figure 1. Intense geomagnetic storm event associated with corotating flows observed during 25/04/89 – 01/05/89 and their association with interplanetary parameters such as solar wind velocity, IMF B and IMF B_Z.

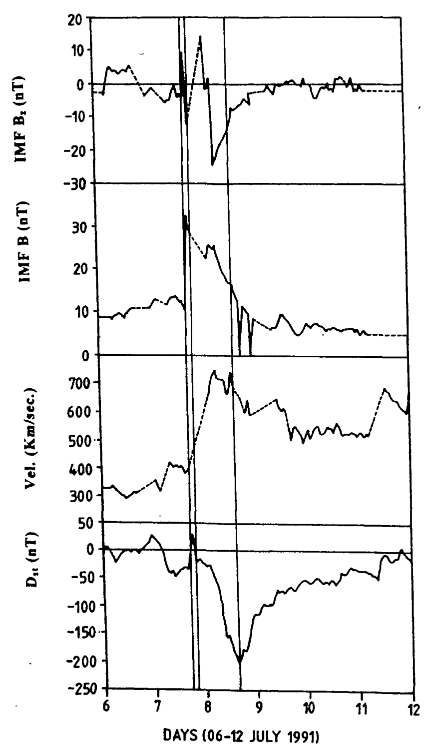

Figure 2. Intense geomagnetic storm event associated with transient disturbances observed during 08/07/91 – 12/07/91 and their association with interplanetary parameters such as solar wind velocity, IMF B and IMF B_Z.

caused by corotating flows, containing peak magnitude -132 nT, initial phase duration -07 hrs., main phase duration -13 hrs. and recovery phase duration -130 hrs. The association of this storm event with solar wind velocity (SWV), interplanetary magnitude (IMF B) and north-south component (IMF B_z), is plotted in Figure 1. During the main phase of this storm solar wind speed and IMF magnitude peaking around 661 kms^{-1} and 22.5 nT respectively. The northward IMF B_2 turned its value from 4.8 to - 11.6 before ousch of main phase. The rather storm event observed on 8-7-91 was caused by transient disturbances, containing peak magnitude –198 nT, initial phase duration –02 hrs., main phase duration – 19 hrs. and recovery phase duration – 198 hrs. The association of this storm event with solar wind velocity (SWV), interplanetary magnitude (IMF B) and north-south component (IMF B_z), is shown in **Figure 2.** During the main phase of this storm, solar wind velocity and IMF magnitude peaking around 747 kms^{-1} and 32.5 nT respectively. The northward IMF B_z turned its value from 9.5 to –12.2 before onset of main phase.

From the above studies, it is concluded that during the initial phase of storm associated either with corotating flows or transient disturbances show same trends of variation of solar wind velocity, interplanetary magnetic field magnitude and northward turning of IMFs. So it is clear that the onset of initial phase is invariant with solar wind streams. Similarly the main phase of geomagnetic storm starts after increasing in IMF B magnitude and solar wind speed, and turning of IMF B_z from northward to southward for both kinds of solar wind flows associated with geomagnetic storms.

The recovery phase duration depends upon decreasing trend on magnitude of solar wind stream and interplanetary magnetic field. In general, north-south component continuously turned during this phase. In our case study ~ event 1 ~ large recovery phase duration (130 hours), IMF B magnitude show decreasing trend while solar wind speed shows increasing trend. The large southward IMF B_z is present during recovery phase. We conclude that the large solar wind velocities in the presence of even moderate southward IMF B_z, can extend the recovery phase of the storm to around 130 hours by maintaining the D_{st} values as high as – 60 nT. This would not have been possible in the presence of northward IMF B_z, inspite of high solar wind velocities. We can explain this result by storm event 2, which is shown in **Figure 2.** This storm is similar to the previous case, but has presence of large solar wind velocities and northward directed IMF B_z during recovery phase. During recovery phase of this storm comparatively higher magnitude (– 198 nT) in comparison as in the previous case recovered within 69 hours in the presence of higher solar wind velocity.

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