Solar causes of geomagnetic storms

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Two hundred ninety nine geomagnetic storms (GMSs) of moderate, moderately severe and severe type with \( A_p \geq 20 \) have been investigated for the period 1978-99 and their possible interplanetary and solar causes are looked upon. Solar features like \( H_a \), X-ray solar flares and active prominences and disappearing filaments (APDFs) have been found to occur more in lower heliographic latitudinal zones and produce larger number of GMSs at various locations on the earth. No significant correlation between magnitude of GMSs and importance of \( H_a \) and X-ray solar flares and APDFs has been observed. Maximum number of GMSs is associated with importance SF of each \( H_a \) and X-ray solar flares. On the basis of the statistical sampling of four putative solar causes of GMSs on the earth, the causes are identified leading to magnetic disturbance with \( A_p \geq 20 \). The \( H_a \), X-ray solar flares are more plausible causes of GMSs. However, a very few GMSs have been observed without being associated with either of these four solar features. The occurrence of disturbed days varies with seasons. Further, monthly distribution of disturbed days shows a cyclic variation having two peaks during the solar cycle.

I Introduction

Geomagnetic disturbances are generally represented by geomagnetic storms and sudden ionospheric disturbances (SIDs). These can be distinguished in two categories which are originated from two types of solar wind streams\(^1\). The first category of geomagnetic storms, known as gradual storm commencement (GSC), arises from magnetically open, long lived, high speed solar wind streams (HSSWS) emitted by solar coronal holes and is usually small in magnitude and exhibits an apparent tendency to occur with 27 days rotation period of the sun\(^2\). The second category of geomagnetic storms is associated with flare generated stream, known as sudden storm commencement (SSC) or sudden impulses (SI). This is relatively large in magnitude and arises from the transient eruption of closed field solar regions and it is identified as abrupt change in general level of geomagnetic field which may be as large as several per cent of the undisturbed value measured at the surface. Thus, SSCs are caused by shock waves propagating through the interplanetary medium from the sun. Subsequently, Sonett et al.\(^3\) reported from direct interplanetary observations that a shock like discontinuity is moving from the sun and is associated with SSC. Burlaga and Ogilvie\(^4\) have discussed some of the events associated with shocks for which both plasma and magnetic field data are available. Nishida\(^5\) suggested that SSC could also be produced by a non-shock mode, presumably, a hydromagnetic wave or a tangential discontinuity, and the non-shock mode discontinuity may be the cause of SI. Sonett and Colburn\(^6\) proposed that SI is due to a reverse shock. Gosling et al.,\(^7\) based on interplanetary observations, have established that an SI might be caused by a non-shock mode discontinuity. Ogilvie et al.,\(^8\) observed a discontinuous decrease in density and discontinuous increase in magnetic field intensity and no appreciable change in temperature, showing that the negative impulses (SI\(^-\)) are caused by hydromagnetic discontinuity whose signature is that of a tangential discontinuity, and the positive impulses (SI\(^+\)) are, some times, caused by hydromagnetic discontinuities.

The solar flare is a most spectacular short-lived phenomenon that occurs on the solar disc and is responsible for solar energetic particle (SEP) event and geomagnetic storm. Solar flares transform magnetic energy into several forms. Large solar flares occur in magnetically complex region, where the field
is often strongly sheared. The mechanism of energy release is probably associated with magnetic reconnection. There are two basic phenomena that occur during magnetic reconnection in the flare site. One of them is rapid heating of coronal and chromospheric material, which expands outward into interplanetary medium and produces interplanetary (IP) shocks which cause geomagnetic storms and auroras. The other phenomenon is associated with particle acceleration, which represents the energy aspect of the flares. Many workers have shown the association of different types of geomagnetic storms with solar flares

The occurrences of flares and prominences are associated with varying phases of sunspot cycle. The solar output in terms of particle and field ejected out into interplanetary medium influences the geomagnetic field conditions. The radiant electromagnetic and corpuscular radiation produce extra ionization in the sun-lit part of the earth and produces disturbances at various locations, such as, solar midlatitude and equatorial regions. These geomagnetic disturbances are observed and represented by different geomagnetic indices like AE, Kp or Ap and equatorial index Dst. The product of solar wind velocity (V) and interplanetary magnetic field (B), i.e., VB is more important for both cosmic ray and geomagnetic activity modulations rather than the IMF alone.

The solar disappearing filaments (DFs) have been linked with geomagnetic activity and also IP shocks. The CMEs related shocks accelerate solar energetic particles (SEPs) events associated with major IP disturbances or shocks causing large geomagnetic storms. An important paradigm shift, such that the CMEs and not flares are considered to be the key causal link between the solar activity and all large geomagnetic storms and the associated effects such as auroral displays, has been reported by Webb. The CMEs are vast structures of solar plasma and magnetic fields which are expelled from the sun into the heliosphere and make a prime link between solar and geomagnetic activity. The north-south component (Bz) of IMF, plays a dominant role in determining the amount of solar wind energy to be transferred to the magnetosphere. When IMF has large magnitude (≥ 10 nT) and large southward component, the amount of transferred energy becomes very large. On the other hand, the transferred energy becomes very small when IMF is directed preliminary northward. The energy transfer efficiency is of the order of 10% during intense magnetic storms. 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. have examined the interplanetary and solar causes of five largest geomagnetic storms during the period 1971-1986 and found that the extreme values of the southward IMF (Bz) rather than the solar wind speeds are the primary causes of great magnetic storms. In this paper, an attempt has been made to examine the effects of solar and interplanetary transients that may cause GMS. Further, the GMS and their association with various phases of sunspot transients and different interplanetary and solar features have been investigated for the period of study.

2 Data analysis

All those geomagnetic storms which are associated with Ap≥20 during the period Jan. 1978-Dec. 1999 are considered and are found to be 299 in number. For this study, solar wind plasma (SWP) and interplanetary magnetic field (IMF) data from IMP-8 satellite are used. These data are compiled by King and Papitashvili in different volumes of Interplanetary Medium Data Book from National Space Science Data Centre (NSSDC). The possible association of geomagnetic storms has been investigated during the period Jan. 1978-Dec. 1993. For association of geomagnetic storms with solar features, solar geophysical data are used. The solar wind velocity (V), solar features have been investigated such that 1 ≤ Δt ≤ 5 days prior to the occurrence of GMS on the earth. Here the time (Δt) taken by the solar wind in reaching the earth from the sun will depend upon the solar wind velocity (V). Further, the occurrence frequency of geomagnetic storms and disturbed days with sunspot cycle is considered for the entire period of consideration, i.e., 1978-99.

3 Results and discussion

The geomagnetic storms with planetary index Ap≥20 have been investigated for the period 1978-99 using solar geophysical data reports. The classification of the selected 299 geomagnetic storms in different varying range of horizontal component of earth’s magnetic field (H) with Ap≥20 and A2 indices are presented in Tables 1 and 2, respectively.
The yearly occurrence of geomagnetic storms with $A_p \geq 20$ and their association with various phases of sunspot cycles are shown in Fig. 1. A close association between yearly occurrence of geomagnetic storms and sunspot cycle is apparent from Fig. 1. Somehow, a peculiar result is also observable during the year 1991, i.e., the SSNs decrease slowly with rapid decrease in the number of storms. No definite trend is established between the SSNs and the GMSs for this case. Solar output influences the earth's magnetic field and produces geomagnetic disturbances at various locations. These disturbances, on the basis of daily average value of $A_p \geq 20$, are being examined and 1888 disturbed days are found during the period 1978-99. The yearly occurrence of disturbed days and their variation with sunspot cycle are presented in Fig. 2. No distinct association between yearly occurrence of disturbed days and sunspot cycle is observed from this analysis. It is not always necessary that the number of disturbed days are maximum during the solar maximum period.

A peculiar result has been observed during the years 1982 and 1993 when disturbed days have increased significantly, whereas, SSNs have decreased. A frequency occurrence histogram of monthly distribution of number of disturbed days with $A_p \geq 20$ during the period 1978-99 has been shown in Fig. 3. It is apparent from Fig. 3 that the maximum number of disturbed days have occurred during the months of March-April and September-October. It is also observed that these distributions show a cyclic variation having two peaks during the solar cycles 21, 22 and 23. Further, monthly distribution of disturbed days on year-to-year basis during the period 1978-99 has been plotted in Fig. 4. A recurrent/periodic occurring tendency of disturbed days with seasons is clearly seen from Fig. 4.

All those geomagnetic storms with $A_p \geq 20$ are considered during the period 1978-93 to investigate their association with solar features. The association of geomagnetic storms with importance of $H_a$ solar flares and X-ray solar flares during the period 1978-93 has been shown in Fig. 5 [(a) and (b)]. From Fig. 5(a), it is apparent that out of 106 GMSs, 83.5% of geomagnetic storms are associated with $H_a$ solar flares of importance $\leq 1N$. Further, it is evident from Fig. 5(a) that maximum number of GMSs are associated with $H_a$ solar flares of importance SF.
Fig. 3 — Histograms showing the monthly average of the number of disturbed days with $Ap \geq 20$ for the entire period from 1978-99

Fig. 4 — Plots showing the year-to-year disturbed days with $Ap \geq 20$ for the entire period 1978-99

(solar flare faint) and SN (solar flare normal); and no significant correlation between magnitude of GMS and importance of $H_s$ solar flare is observed. Further, it is apparent from Fig. 5(b) that out of 70 geomagnetic storms, 85.7% of GMSs are associated with X-ray solar flares of importance $<1N$. Further, it is quite evident from Fig. 5(b) that maximum number of GMSs are associated with X-ray solar flares of importance SF and SN. Again, no significant correlation between magnitude (intensity) of

Fig. 5 — Histograms showing the occurrence frequency of the importance of (a) $H_s$ solar flares and (b) X-ray solar flares for the period 1978-93
geomagnetic storm and importance of X-ray solar flares has been observed. Sometimes, the X-ray solar flares of lower importance are also able to produce GMSs. This may be due to X-ray burst (II, IV radio burst), larger size and more active National Oceanic and Atmospheric Administration (NOAA) region, more duration and lower helio-latitude / longitude of X-ray solar flares. Actually, solar flares of higher importance are able to produce fast IP shocks in interplanetary medium which cause the large geomagnetic storms. The magnitude of GMSs is associated with two kinds of IP shocks known as fast and slow IP shocks. These fast and slow IP shocks are associated with different properties of solar flares, e.g. occurrence duration, area, NOAA region and location (helio-longitude/latitude) of solar flares. In that case, sometimes solar flares of lower importance which are associated with fast shocks, may produce more intense geomagnetic storms. But, no significant correlation between magnitude of GMSs and importance of solar flares is observed. A frequency occurrence histogram of GMSs with helio-latitude / longitude of Hα solar flares has been plotted in Fig. 6 [(a) and (b)]. From Fig. 6(a), it is evident that 52.8% geomagnetic storms is produced by eastern Hα solar flares and 72.6% is produced by western Hα solar flares and 48.1% is produced by southern Hα solar flares and most effective latitudinal zone for producing geomagnetic storms is (0-40)°S. At the helio-latitude in the range (0-30)°N and (0-30)°S, there is a concentration of 94.3% of the total Hα solar flares associated with GMSs and no storm is produced by Hα solar flare beyond 40°N and 40°S. Further, it is quite apparent from Fig. 6(b) that 51.8% geomagnetic storms is produced by western Hα solar flares and 48.1% is produced by eastern Hα solar flares. Again, 72.6% geomagnetic storms is produced by Hα solar flares of helio-longitude between 0° and 60°E and between 0° and 60°W. Thus, it may be deduced that Hα solar flares occurred within lower heliographic latitude produce maximum number of GMSs. Therefore, the Hα solar flares occurred within lower heliographic latitude are able to produce a configuration of closed magnetic field regions, which may be associated with IP shocks in the interplanetary medium leading to cause GMSs on the earth. On the higher heliographic latitudes, Hα solar flares have not occurred in association with GMSs.

The association of GMSs with different heliographic zones of X-ray solar flares is also investigated. Frequency occurrence histogram of GMSs with helio-latitude/longitude of active prominences

![Fig. 6](image-url)
and disappearing filaments (APDFs) during the period 1978-93 have been plotted in Fig 8(a) and (b). It is observed from Fig. 8(a) that 54.7% geomagnetic storms are produced by northern APDFs and the most effective helio-latitude zones for producing GMSs lie between 0° and 40°N. At helio-latitude (0-40)° N and S, there is a concentration of 92.8% of total APDFs that are associated with GMSs and no storm is produced by APDFs beyond 50°N and 60°S. Further, it is quite evident from Fig. 8(b) that almost equal number of GMSs are produced by each eastern and western APDFs solar features. It is observed from Fig. 8(b) that 55.9% GMSs is produced by APDFs in heliographic longitude range 0-60°E and 0-60°W. Thus, it may be inferred that the APDFs, occurred within lower heliographic latitudinal zones, produce maximum number of geomagnetic storms.

Finally, the association of significant GMSs (216) with $A_p \geq 20$ which are investigated during the period 1978-93 with various solar activities is discussed. Association of these GMSs during the said period has been plotted using Venn diagram in Fig. 9. It is quite clear from Fig. 9 that 106, 70, 84, 30 geomagnetic storms are associated with each $H_a$ solar flares, X-ray solar flares, APDFs and CMEs, respectively. It is observed that maximum number of GMSs seem to be associated with solar flares ($H_a$ and X-ray solar flares), because solar flares occur more frequently than prominence eruptions. This agrees with the Garcia and Dryer10 results and is inconsistent with the results of Hewish and Bravo19 and Webb25. The prominence eruptions have occurred on an average of about 0.55/day, during 1976-1979, while solar flares have occurred at the rate of 1.19/day during the period 1978-1979 (Ref. 13). Associations of GMSs with different combination of solar features, i.e., $H_a$, X-ray solar flares, APDFs and CMEs have been shown in Fig. 9. It is also observed from Fig. 9 that six GMS are not associated with any solar features, revealing that some solar phenomena occurred on the back portion of solar disc which could not be seen during the observation, have caused the geomagnetic storms.

4 Conclusions

From the present statistical analysis of the GMSs for the period 1979-99, the following conclusions may be drawn:

- Solar flares, APDFs and CMEs are the primary causes of geomagnetic storms.
- Maximum number of geomagnetic storms are produced by northern APDFs.
- The most effective helio-latitude zones for producing GMSs lie between 0° and 40°N.
- The concentration of GMSs is highest in the heliographic longitude range 0-60°E and 0-60°W.
- Solar flares occur more frequently than prominence eruptions, which agrees with the Garcia and Dryer results.
- Some solar phenomena occurred on the back portion of the solar disc, which could not be seen during the observation, have caused the geomagnetic storms.
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