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Study of solar features causing GMSs with $250\gamma < H < 400\gamma$

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Abstract. The effect of solar features on geospheric conditions leading to geomagnetic storms (GMSs) with planetary index, $A_{\rm p} \geq 20$ and the range of horizontal component of the Earth's magnetic field H such that $250\gamma < H < 400\gamma$ has been investigated using interplanetary magnetic field (IMF), solar wind plasma (SWP) and solar geophysical data (SGD) during the period 1978–99. Statistically, it is observed that maximum number of GMSs have occurred during the maximum solar activity years of 21st and 22nd solar cycles. A peculiar result has been observed during the years 1982, 1994 when sunspot numbers (SSNs) decrease very rapidly while numbers of GMSs increase. No distinct association between yearly occurrence of disturbed days and SSNs is observed. Maximum number of disturbed days have occurred during spring and rainy seasons showing a seasonal variation of disturbed days. No significant correlation between magnitude (intensity) of GMSs and importance of H_α, X-ray solar flares has been observed. Maximum number of GMSs is associated with solar flares of lower importance, i.e., SF during the period 1978–93. H_α, X-ray solar flares occurred within lower helio-latitudes, i.e., (0–30)°N to (0–30)°S are associated with GMSs. No H_α, X-ray solar flares have occurred beyond 40°N or 40°S in association with GMSs. In helio-latitude range (10–40)°N to (10–40)°S, the 89.5% concentration of active prominences and disappearing filaments (APDFs) are associated with GMSs. Maximum number of GMSs are associated with solar flares. Coronal mass ejections (CMEs) are related with eruptive prominences, solar flares, type IV radio burst and they occur at low helio-latitude. It is observed that CMEs related GMS events are not always associated with high speed solar wind streams (HSSWSs). In many individual events, the travel time between the explosion on the Sun and maximum activity lies between 58 and 118 h causing GMSs at the Earth.

Keywords. Geomagnetic storm; solar flares; active prominences and disappearing filaments; coronal mass ejections; helio-latitude; helio-longitude; sunspot numbers.

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1. Introduction

Sunspots are the most obvious features of disturbed surface of the photosphere in the solar atmosphere and play a key causal role in major geomagnetic disturbances. When these disturbances encounter the Earth they interact with the magnetosphere causing geomagnetic storms (GMSs) and are associated with ionospheric effects and ground level enhancements

(GLEs). The sunspots may divide or merge and a single spot or a bipolar pair may rotate; such motion may produce the occurrence of a flare. Large solar flares occur in magnetically complex region where the field is often strongly sheared. The mechanism of release of energy is associated with magnetic reconnection. GMSs can be distinguished into two kinds originating from two types of solar wind streams [1]. The first kind, gradual storm commencements (GSCs) arising from magnetically open and long-lived high speed solar wind streams (HSSWSs) emitted from coronal holes are usually small in magnitude and exhibit an apparent tendency to recur with 27 days rotation period of the Sun [2]. The second kind, i.e., sudden storm commencements (SSCs) are associated with flare/CME generated ejecta. SSCs are relatively large in magnitude. The southward component of interplanetary magnetic field (IMF), B_z is an important parameter for the development of GMS [3,4].

The occurrence of prominence and flare is also associated with varying phases of sunspot cycle and leads to geomagnetic disturbances causing GMSs. The solar output in terms of particle and field ejected out into interplanetary medium influences the geomagnetic fields [5–7]. The solar flares are the most spectacular short-lived phenomena that occur on the solar surface and are responsible for solar energetic particles (SEPs) events. Solar flares transform magnetic energy into several forms. Most of the interplanetary (IP) shock waves originate at or near the Sun in a particular form of an active region. The entire shock disturbances may engulf the Earth and the various phases of GMSs are produced [8].

Over the past half-century, it is thought that solar flares are responsible for major interplanetary particle events (IPEs) and GMSs [9]. On the other hand, it is found that GMSs are more associated with coronal holes than the solar flares [10]. GMSs are also associated with either a compound stream or a magnetic cloud [11,12]. There is statistical evidence favouring the association of GMSs with the magnetic clouds produced by coronal mass ejections (CMEs) [10,13,14]. Strong geomagnetic disturbances are associated with passage of magnetic cloud causing GMSs [15–23].

Recently, it is observed that CMEs are the key causal link to solar activity that produce GMSs [24]. Further, interaction between slow and fast solar wind (from coronal holes) creates corotating interaction regions (CIRs), a phenomena brought out into prominence again by Ulysses observations. The effect of CIRs on cosmic rays received new attention in recent years [25] and is realized that CIRs are much more dominant features in the heliosphere than previously anticipated. Data available from Skylab mission suggest that the coronal holes, CMEs, erruptive prominence and disappearing filaments (EPDFs) and solar flares have causal link with solar activity and energy emitting region and they produce GMSs. Although there has been substantial growth in our knowledge of solar and interplanetary features leading to cases of GMSs, there are still unanswered questions that must be addressed and solved to predict the occurrence of GMSs [26,27]. In this paper a detailed analysis of GMSs has been presented and an attempt has been made to understand the association of GMSs with different solar transients.

2. Data analysis

In the present analysis, all the GMSs which are exclusively SSCs and are associated with $250\gamma < H < 400\gamma$ along with $A_{\mathrm{p}} \geq 20$ are being considered using SGD, SWP data and IMF data during the period 1978–93 [28]. Out of the 81 GMSs, 65 GMSs have occurred during the period 1978–1993 and 16 GMSs have occurred during the period 1994–1999. However, the possible association of these events with solar features have been investigated from 1978–93. Variations of GMSs with SSNs have been investigated from 1978 to 1999. The position of solar features, e.g., H_α, X-ray solar flares and active prominences and disappearing filaments (APDFs) have been observed 58–118 h prior to the occurrence of SSC at the Earth depending upon V [29]. Different authors define the severity of GMSs by taking different parameters. Garcia and Dryer [9] have said a storm is considered minor if $30 < A_\mathrm{p} < 50$, major if $50 < A_\mathrm{p} < 100$ and severe if $A_\mathrm{p} > 100$. Gonzalez and Tsurutani [30] have considered intense GMSs for which $D_\mathrm{st} < -100$ nT with North–South component of interplanetary magnetic field, $B_z < -10$ nT; whereas, Kohli *et al* [31] have said that a storm is considered moderate if $H < 250\gamma$, moderately severe if $250\gamma < H < 400\gamma$ and severe if $H > 400\gamma$ [30,31].

3. Results and discussion

When identifying the part of sporadic phenomena on the solar disc with the source that is responsible for SSC at the Earth, it is possible to show, according to Ivanov *et al* [32], the time $\Delta t = t_\mathrm{sc} - t_\mathrm{sp}$ taken by a shock wave to propagate from the Sun to the Earth lies in the interval 0.5 days $< \Delta t <$ 5 days (here t_sp is the time of the sporadic event occurring on the Sun and t_sc is the time of the associated SSC appearing at the Earth), then only those sporadic events which have occurred before SSC within this interval Δt may be its source. The limiting interval Δt, in considering each individual case, may be deduced substantially and therefore, an SSC becomes identifiable with its source more accurately, if the shock wave velocity throughout most of the distance from the Sun to the Earth remains uniform if it is taken into consideration. Hewish and Bravo [10] using the same criteria found that Δt is varying between 1 and 6 days and identified 96 disturbances. However, in our study Δt is lying between 58 and 118 h. Transient, radiative and corpuscular emission from the Sun associated with solar features produce outstanding disturbances in the environment of the Earth [33] which causes GMSs at various locations of the Earth such as, polar, mid-latitude and equatorial regions. These GMSs are observed and represented by equatorial index D_st and different planetary indices K_p and A_p. Yearly occurrence of GMSs and their association with sunspot numbers have been plotted in figure 1 during the period 1978–99. When the solar activity periods are maximum and minimum, statistically the GMSs are observed to be $\simeq$75% and 25% respectively. This is true for both the 21st and 22nd solar cycles. Thus, it is evident that maximum number of GMSs have occurred during maximum activity years of 21st and 22nd solar cycles. A peculiar result has been observed during the years 1982 and 1994 when sunspot numbers decrease rapidly while GMSs increase significantly. Thus, it is evident that the Sun is more active for producing large number of GMSs during the years 1982 and 1994 respectively. The number of GMSs are significantly larger during the solar activity years 1989 and 1990. Yearly occurrence of disturbed days with $A_\mathrm{p} \geq 20$ and their variation with sunspot numbers has been plotted in figure 2 and it is found that the total number of disturbed days during the period 1978–99 are 1888. No distinct association between yearly occurrence of disturbed days with SSNs is observed from this analysis. Somehow, the number of disturbed days have occurred larger during the year 1982, 1991 and 1993. A peculiar result has been observed during the years 1982 and 1993 when SSNs decrease rapidly whereas number of disturbed days increase drastically which shows that

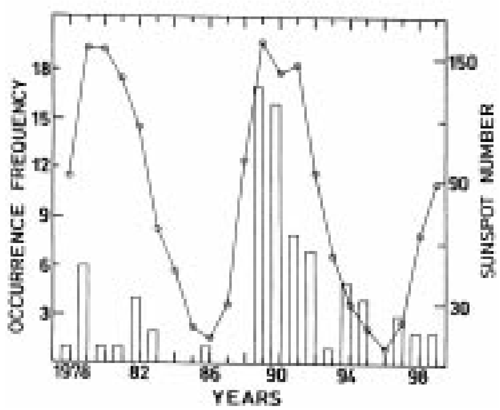

Figure 1. The occurrence frequency of the geomagnetic storms and sunspot numbers have been plotted histographically for the period 1978–99.

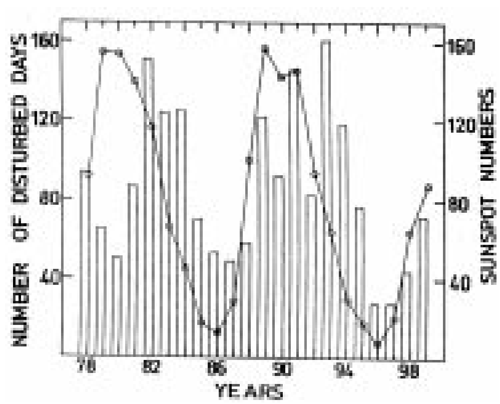

Figure 2. The number of disturbed days with $A_{\rm p} \geq 20$ and sunspot numbers have been plotted histographically for the period 1978–99.

the Sun is more active during the years 1982 and 1993. A frequency occurrence histogram of monthly disturbed days ($A_{\rm p} \geq 20$) has been plotted for the period 1978–99 in figure 3. From figure 3, it is evident that maximum number of disturbed days are found in the months of spring and rainy seasons which shows that the number of disturbed days are likely to vary with seasons. It is also observed that these distributions show a cyclic variation having two peaks during each solar cycle in consistence with earlier findings [34].

A frequency occurrence histogram of importance of H_α, X-ray solar flares have been plotted in figure 4a, b respectively. It is observed from figure 4a that 56%, 28% and 16% of H_α solar flares with importance SF, SN and $>$ 1N are associated with GMS respectively. Further, from figure 4b, it is evident that 56.2%, 12.5%, 31.2% of X-ray solar flares of importance SF, SN and $>$ 1N are associated with GMSs respectively. No significant correlation between magnitude (intensity) of GMS and importance of H_α, X-ray solar flares has been observed. It is statistically observed that maximum number of GMSs are associated with importance SF of each H_α, X-ray solar flares. A number of workers [35–37]

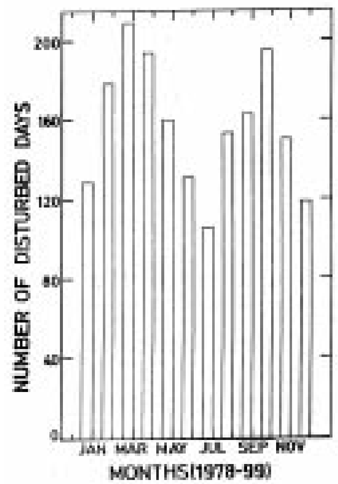

Figure 3. The monthly average of the number of disturbed days with $A_p \geq 20$ for the entire period 1978–99 have been plotted histographically.

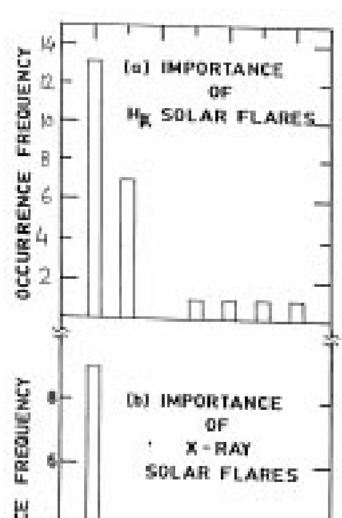

Figure 4. The occurrence frequency of the importance of (**a**) H_α solar flares and (**b**) X-ray solar flares have been plotted histrographically for the period 1978–93.

have shown the association of different types of GMSs with solar flares and suggested that the solar flares of higher importance can produce large (intense) GMSs. However, based on our findings, in some of the cases, the solar flares of lower importance in association

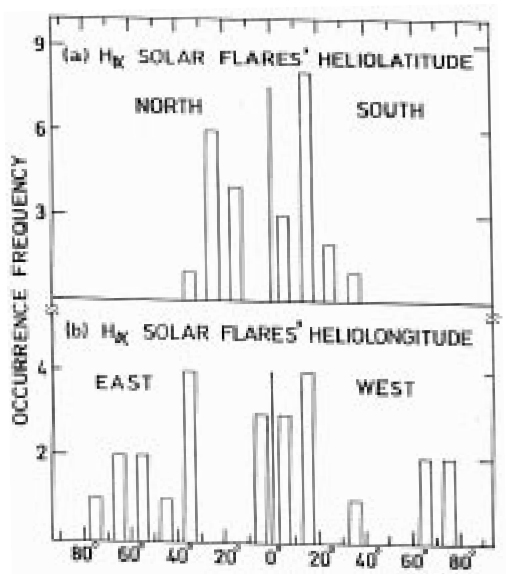

Figure 5. The occurrence frequency of the H_α solar flares with (**a**) helio-latitude and (**b**) helio-longitude have been plotted histographically for the period 1978–93.

with some other specific properties, i.e., location, region, duration of occurrence may also cause intense GMSs. A frequency occurrence histogram of H_α, X-ray solar flares and APDFs with different helio-latitude (North–South) and longitude (East–West) associated with different GMSs have been plotted for the period 1978–93 in figures 5a, 5b, 6a, 6b and 7a, 7b respectively. It is observed from figure 5a that 44% and 56% H_α solar flares occurring in the northern and the southern helio-latitude are associated with GMSs and the most effective zone for producing H_α, solar flares lie between (0–30)°N and (0–30)°S. At the helio-latitude in the range (0–30)°N to (0–30)°S, there is concentration of 92% of the H_α solar flares associated with GMSs type and no H_α solar flares occurred beyond 40°N and 40°S. It is observable from figure 5b that 52% and 48% H_α solar flares have occurred in the eastern and the western helio-longitude range respectively. Further, at helio-longitude in the range (0–60)°E to (0–60)°W, there is concentration of 72% H_α solar flares which are associated with GMSs. Remaining 28% H_α solar flares are distributed over the range (60–90)°E to (60–90)°W. Thus, it may be derived from here that H_α, solar flares occurring within lower heliographic latitude are associated with GMSs. Furthermore, it is observed from figure 6a that 75%, 25% X-ray solar flares occurring in northern and southern heliographic latitude are associated with GMSs and the most effective latitudinal zone for producing X-ray solar flares lies between (0–30)°N to (0–30)°S and are associated with GMSs. At helio-latitude in the range (0–30) °N to (0–30)°S, there is concentration of 81.2% of X-ray solar flares associated with GMSs. No X-ray solar flares have occurred beyond 40°N and 40°S in association with GMSs. From figure 6b, it is evident that 62.5% and 37.5% X-ray solar flares occurring in eastern and western heliographic longitude are associated with GMSs. Further, 93.7% X-ray solar flares occurring within heliographic longitude range (0–60)°E to (0–60)°W are associated with GMSs. Thus X-ray solar flares occurring within lower heliographic latitude are associated with GMSs. It is evident from

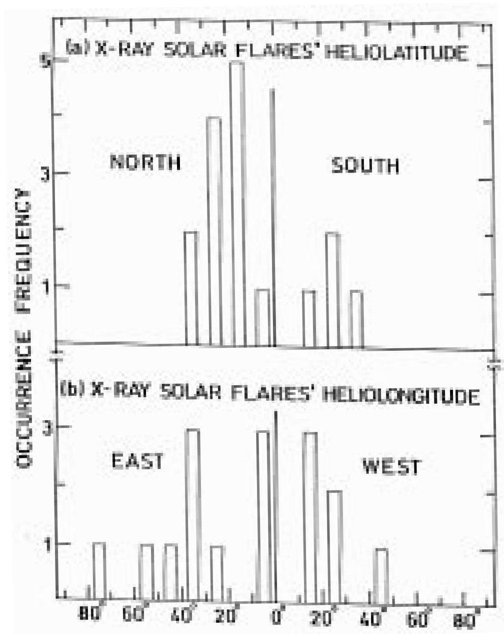

Figure 6. The occurrence frequency of the X-ray solar flares with (**a**) helio-latitude and (**b**) helio-longitude have been plotted histographically for the period 1978–93.

figure 7a that 63.1% and 36.9% APDFs occurring in northern and southern helio-latitude are associated with GMSs respectively. The most effective zone for producing APDFs lies between (10–30)°N and (10–30)°S and are associated with GMSs. At the helio-latitude range (10–30)°N to (10–30)°S, there is concentration of 89.5% of APDFs associated with GMSs and no APDFs have occurred beyond 60°N or 60°S. Further, figure 7b shows that 52.6% and 47.4% APDFs occurring in eastern and western helio-longitude range are associated with GMSs respectively. A peculiar result has been observed where 31.5% APDFs have occurred in the helio-longitude range (80–90)°E to (80–90)°W of the entire period under consideration. Furthermore, 57.8% APDFs occurring in the helio-longitude range (0–60)°E and (0–60)°W are associated with GMSs. Thus, it may be inferred that larger APDFs occur in lower heliographic latitude range.

The association of GMSs with solar features, i.e., H_α, X-ray solar flares, APDFs and CMEs has been plotted in figure 8. It is quite apparent from figure 8 that 71.5%, 45.7% and 54.3% GMSs are associated with H_α, X-ray solar flares and APDFs respectively. Further, it is observable from figure 8 that ten GMSs are not associated with any solar features. This shows that some solar features are occurring on the back side of the solar disc which are not photographed, and are also contributing for this cause. In case of individual events the travel time between the explosion on the Sun and maximum activity causing GMS at the Earth lies between 58 and 118 h. Statistically, it is found that CMEs are equally related with H_α solar flares and APDFs. Thus, it is concluded that GMSs are more associated with solar flares than with other solar features. This result is consistent with Garcia and Dryer [9]. Some solar flares do, in fact, play a fundamental role in generating CMEs leading to cause

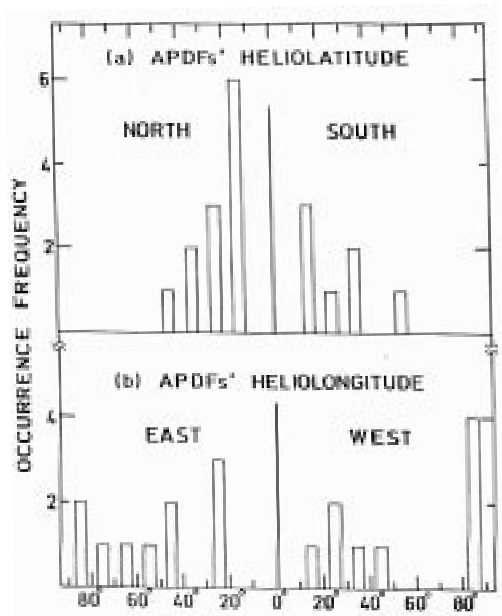

Figure 7. The occurrence frequency of the APDFs with (**a**) helio-latitude and (**b**) helio-longitude have been plotted histographically for the period 1978–93.

GMSs [38]. It is observed that V related to CME's event is > 400 km/s. CMEs are related with radio burst IVth type. Type IV radio burst is associated with solar flares as well as APDFs. Both CMEs driven shock and flare associated blast wave is a possible cause of type IV radio emission. Similar result has been obtained by Kaiser *et al* [39]. Klassen *et al* [40] found that type II, IV burst source appears in between two high soft X-ray loop system, and also appears at different sites above the H_α flare [40]. The onset of CMEs can be associated with both flares and filaments [41]. Latest studies show their most common association with eruptive prominence rather than with flares. Recently, it is believed that the Sun generates magnetic flux tubes at the base of the convection zone and transport them to the surface via the mechanism of magnetic buoyancy. A build-up of magnetic flux in the corona is unavoidable unless all the magnetic flux brought to the surface is somehow returned below the photosphere. This magnetic flux expands outward in the form of prominence and sometimes it disappears from the corona in an explosive manner. By these processes the Sun expels magnetic flux into the interplanetary space and 10^{12}–10^{13} kg of solar plasma is suddenly propelled outward into the interplanetary space. Ejection speed within 5 solar radii of the Sun's surface ranges from less than 50 km/s in some of the slower events to as high as 1200 km/s in some of the faster events [42,43]. It is statistically found that CMEs are found in different sizes and they mostly occur at low latitudes. Similar result has been obtained by Hundhausen [44]. Some important characteristics of CMEs observed by satellite borne coronagraph are: CMEs can release the energy to an extent of $\sim 10^{30}$–10^{32} erg which is comparable to or exceeds the energy contents of a flare. They involve the expansion of about 10^{15}–10^{16} g of material from the corona at speeds of 10 km/s to over 1000 km/s [45]. The origin of these events can be clearly associated with

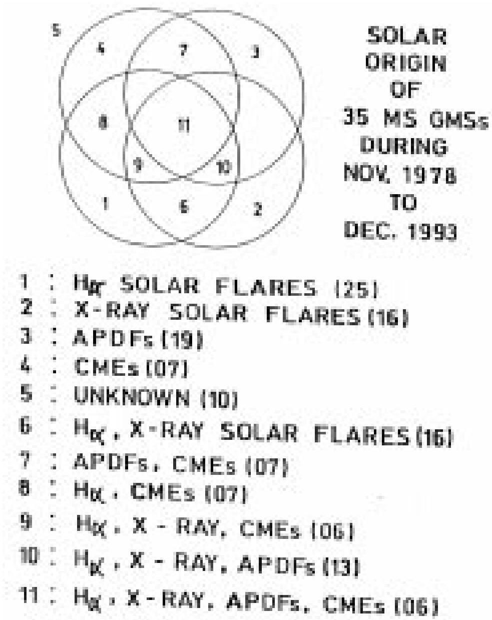

Figure 8. The solar origin of 35 geomagnetic storms with $A_{\rm p} \geq 20$ and with $250\gamma < H < 400\gamma$ have been plotted using Venn diagram during the period Jan. 1978–Dec. 1993.

other active features such as flares, active regions and prominences both statistically and on an individual basis. Similar result has been obtained by Harrison *et al* [46]. The value VXB directly modulates the geomagnetic activity. The product VXB is more important for geomagnetic activity rather than IMF alone [47].

4. Conclusions

From the rigorous analysis of data presented in the foregoing section, the following conclusions are drawn:

(i) 75% and 25% GMSs are observed during maximum and minimum activity years of the 21st solar cycle respectively whereas, 73.2% and 26.8% GMSs have occurred during maximum and minimum activity years of the 22nd solar cycle. A peculiar result has been observed during the years 1982, 1994 when SSNs decrease very rapidly while the number of GMSs increase.

(ii) No distinct association between yearly occurrence of disturbed days and SSNs is observed. Somehow, larger number of disturbed days have occurred during the years 1982, 1991, 1993. Number of disturbed days vary with seasons. The distribution of disturbed days show a cyclic variation during the solar cycles.

(iii) No significant correlation between magnitude (intensity) of GMSs and importance of H_α, X-ray solar flares have been observed. However, the basis of statistical analysis and the larger number of GMSs are associated with solar flares of lower importance, i.e., SF during the period 1978–93. On some occasions, the solar flares with lower importance in association with some other specific properties such as, location, region, duration of occurrence may also cause intense/large/severe GMSs.

(iv) H_α, X-ray solar flares have occurred within lower helio-latitudes, i.e., (0–30)°N to (0–30)°S and helio-longitudes, i.e., (0–60)°E to (0–60)°W associated with GMSs. No H_α, X-ray solar flares have occurred beyond 40°N or 40°S.

(v) In the helio-latitude range (10–40)°N to (10–40)°S, there is 89.5% concentration of APDFs which are associated with GMSs.

(vi) 71.5% GMSs are associated with solar flares. However, few GMSs are not associated with any of the solar features on the visible side of the solar disc.

(vii) CMEs are related with eruptive prominence, solar flares, type IV radioburst and they occur at low helio-latitudes. It is observed that CMEs related GMS events are not always associated with HSSWSs.

(viii) In many individual events, the travel time between explosion on the Sun and maximum activity lies between 58 and 118 h causing GMSs at the Earth.

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