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Geomagnetic storms with $H \geq 400nT$ during 1979-99

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Abstract. The effect of solar features on geospheric conditions leading to ninety nine geomagnetic storms (GMSs) with $H \geq 400$ nT and $Ap \geq 20$ have been investigated using interplanetary magnetic field (IMF), solar wind plasma (SWP) and solar geophysical data (SGD) during the period 1979-99. H_α, X-ray solar flares occured within lower latitudinal zone i.e., 30°N-0-30°S, are associated with maximum number of GMSs. Further, 91.7% of total APDFs occured within helio-latitudinal range 30°N-0-30°S are associated with GMSs. No significant correlation between magnitude (intensity) of GMS and importance of H_α, X-ray solar flares is observed. Magnitude of GMSs is associated with different properties of H_α, X-ray solar flares and APDFs i.e, NOAA region, location (helio-longitude/latitude), duration and area of solar events. It is observed statistically that 77.2%, 62.8% and 68.5% GMSs are associated with H_α, X-ray solar flares and APDFs respectively. It is observed that coronal mass ejection (CMEs) related storm sudden commencements (SSCs) are not always associated with high speed solar wind streams (HSSWS). Associated solar activity of CME events near the Sun are eruptive prominences, long duration solar events, impulsive X-ray events, optical flares, type II and IV radio burst leading to SSCs. The travel time between the explosion on the solar disc and maximum geomagnetic activity has been observed in the range 53-114 Hrs.

Keywords : GMSs, Sunspot Cycle, Solar flares, APDFs, Heliolatitude/longitude. Horizontal Component of Earth Magnetic Field (H).

1. Introduction

Sunspots are most obvious features of disturbed surface of the photosphere on solar atmosphere and play a key causal role in major solar geomagnetic disturbances. The most energetic disturbances of the heliosphere in the vicinity of IAU are interplanetary shocks, accompanied

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by shells of increased density 0.1–0.2AU thick and followed by out flows of enhanced speed (Borrini et al., 1982). These transients are often associated with energetic particles, the flux of which maximizes near the shock passage but may be detected before and after the shock has passed (Vannes et al., 1984). When disturbances encounter the Earth they interact with the magnetosphere causing geomagnetic storms (GMSs) and associated with ionospheric effect and ground level enhancements (GLEs). Large solar flares occur in magnetically complex region where the field is often strongly sheard. The mechanism of release of energy is 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 GMSs and auroras. The other phenomena is associated with particle acceleration, which represents the energy aspect of the flares. The characteristic of a geomagnetic storm is the development of an equatorial ring current caused by the differential drifts of energetic particles in the magnetosphere. This ring current flows clockwise thus producing a decrease in the axial component of the magnetic field measured at low latitudes on the surface of the Earth. The axial component is nearly the same as the horizontal component of Earth magnetic field (H). GMSs can be distinguished into two kinds originated from two kinds of solar wind streams (Feynman and Gu, 1986). The first kind gradual commencement storms (GCSs) arise from magnetically open, longlived high speed solar wind streams (HSSWS) emitted from coronal holes and are usually small in magnitude and exhibit an apparent tendency to recur with 27 days rotation period of Sun (Hundhausen, 1977). The second kind ie. storm sudden commencements (SSCs) associated with flares generated streams. SSCs and sudden impulses (SIs) are caused by hydromagnetic shock waves and discontinuities in the solar wind. The SSCs and streams are associated with either a compound stream or a magnetic cloud. Interplanetary magnetic field (IMF,B) southward component B_z is an important parameter for the development of GMS (Akasofu and Chapman, 1963; Akasofu, 1981).

The solar output in term of particle and field ejected out into interplanetary medium influences the geomagnetic fields (Kahler, 1992; Webb, 1992; Gosling, 1993). The solar flares are most spectacular short lived phenomena that occurs on the solar surface and are responsible for solar energetic particles (SEPs) events and GMSs. Solar flares transform magnetic energy into several forms. Most of the interplanetary (IP) shock waves originate at or near the Sun in the particular from on an active region and when in succession, the entire shock disturbances engulf the Earth and the various phases of GMSs are produced (Akasofu and Chao, 1980). Over the passed half century, it is thought that solar flares are responsible for major interplanetary particle events (IPEs) and GMSs (Garcia and Dryer, 1987). It is found that the GMSs are more associated with coronal holes than the solar flares (Hewish and Bravo, 1986). GMSs are also associated with either a compound stream or a magnetic cloud (Burlaga et al., 1987; Wilson, 1987). There is an evidence favouring statistical association between magnetic clouds and solar activity indicative of coronal mass ejection (CMEs) from coronal holes (Hewish and Bravo, 1986 Wilson and Hildner, 1984, 1986). Strong geomagnetic disturbance is associated with passage of magnetic cloud causing GMSs; (Wilson, 1990; Zhang and Burlaga, 1988; Tsurutani et al., 1988; Gonzalez et al., 1989; Lepping et al., 1991; Farrugia et al., 1993; Gonzalez et al., 1994; Tsurutani and Gonzalez, 1997; Farrugia and Burlaga, 1997).

Recently, it is being observed that CMEs without considering solar flares are the key causal link with solar activity and produce GMSs (Webb, 1992, 1995). 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 (Kunow et al., 1995) and it is realized that CIRs are much more dominant features in the heliosphere than previously anticipated. Data available from sky lab mission suggest that the coronal holes, CMEs, eruptive prominences and disappearing filaments (EPDFs) 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 causes of GMSs, there are still unanswered questions that must be addressed and solved to predict the occurrence of GMS (Tsurutani and Gonzalez, 1995, 1997). In this paper a detailed analysis of GMS has been presented and an attempt has been made to understand the association of GMS with various solar features.

2. Analysis

In present analysis, all those GMSs which are exclusively SSCs and are associated with $A_p \geq 20$ alongwith horizontal component of Earth's magnetic field, $H \geq 400$ nT are being considered using solar geophysical data (SGD), solar wind plasma (SWP) data and interplanetary magnetic field (IMF) data during the period 1979-93 (Couzens and King, 1986, 1989, 1994). These data are measured through IMP-8 satellite. Out of 99 GMSs, 69 GMSs have occurred during the period 1979-93 and 30 GMSs have occurred during the period 1994-99. However the possible association of these events with solar features have been investigated from 1979-93. The positions of solar features e.g. H_α, X-ray solar flares and active prominences and disappearing filaments (APDFs) have been noted 53-114 Hrs prior to the occurrence of SSC at Earth depending upon solar wind velocity (V), solar geophysical data Reps. (1979-93).

3. Results and Discussion

Possible association of GMSs with solar features e.g., solar flares and APDFs have been investigated during the period 1979-93. When identifying the part of sporadic phenomena on the solar disc with source that is responsible for SSCs at the Earth, it is possible to show, according to Ivanov et al. (1982), the time $\Delta t = t_{sc} - t_{sp}$ taken by a shock wave to propagate from the Sun to the Earth lies in the interval 0.5 day $\leq \Delta t \leq$ 5 days (here t_{sp} is the time of the sporadic event occurs on the Sun and t_{sc} is the time of the associated SSC appears at the Earth), then only those sporadic event(s) which have occurred before SSC within this interval Δt may be its source. The limiting interval Δt, in considering each individual case, may be reduced substantially and therefore, an SSC becomes identifiable with its source more accurately, if it is taken into consideration that the shock wave velocity throughout most of the distance from the Sun to the Earth. Hewish et al. (1986) found that Δt time varying between 1 day to 6 days prior to the date arrival is indicated and identified 96 disturbances. But in our study Δt lying between 53 to 114 Hrs. On the above basis, some events with $A_p \geq 20$ and $H \geq 400$ nT are identified, in which Δt is lying between 53 to 114 Hrs. Number of workers (Akasofu and Yoshida, 1967; Lockwood, 1971; Pudovkin and Chertkov, 1976) have shown that the association of different types of GMSs with solar flares and suggested that the solar flares of higher importance can produce large (Intense) GMS. Transient, radiative and corpuscular emission from the Sun associated with solar features, produce outstanding disturbances in the environment of the Earth (Bavassano et al., 1994) which causes GMSs at various location of Earth such as, polar, mid latitude and equatorial regions. These GMSs are observed and represented by different geomagnetic indices A_E, equatorial index D_{st} and planetary index K_p and A_p.

The frequency occurrence histogram of importance of H_α and X-ray solar flares have been plotted in Fig. 1 (a and b) respectively for the period 1979-93. It is observed that 37%, 25.9% and 18.5% GMSs are associated with H_α solar flares of importance SF, SN and 1N respectively, whereas 52.3%, 19% and 14.3% GMSs are associated with X-ray solar flares of importance SF, SN and 1N respectively as shown in Figs 1(a and b) which shows that solar flares of higher

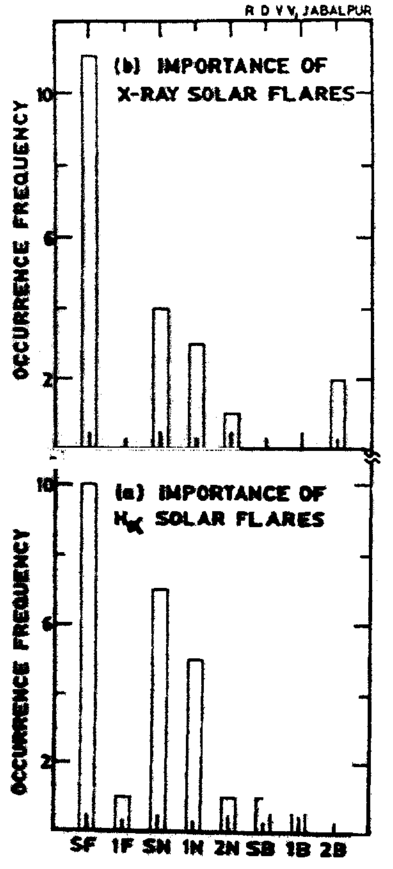

Figure 1. The occurrence frequency of the importance of (a) Hα solar flares and (b) X-ray solar flares have been plotted histographically for the period 1979-93.

importance are not only the cause to be able to produce fast IP shocks in interplanetary medium which causes GMSs. The magnitude (intensity) of GMSs is associated with two kinds of IP shocks known as fast and slow IP shocks. These fast/slow IP shocks are associated with different properties of solar flares eg, location (heliolatitude/heliolongitude), NOAA region, area, shape and occurrence duration of solar flares. In that case, solar flares of lower importance (eg, Jan 15th, 1989; Mar 16th, 1989) which are associated with fast IP shocks may produce more intense GMS associated with D_{st} (-122nT) and D_{st} (-120nT) respectively. The occurrence duration of Jan 15th H_α solar flares in 1989 and Mar 16th, 1989 events is 45 min, although these events are associated with lower importance of H_α solar flares. Therefore, no significant association between magnitude of GMSs and importance of H_α and X-ray solar flares have been found. It is observed that maximum number of GMSs are associated with SF, SN of H_α solar flares and X-ray solar flares. The discrepancy between the number of flares of importance SF and higher and number of SSCs may perhaps be attributed to, for example, the fact that the form of the flare in induced shock front is not a spherically symmetric one but is oblate in one direction (Ivano et al., 1982). Owing to this, if when the shock wave reaches 1AU the Earth finds it self outside the region of the waves action, no SSC will be recorded and vice versa. Ivanov et al. (1982) hypothesized that the oblateness axis of the shock front must be oriented parallel to the N-S line of the magnetic axis of the bipolar groups near which the flare occurred. A frequency occurrence histogram of H_α solar flares with different heliolatitude (North-South) and heliolongitude (East-West) associated with GMSs have been plotted in Fig. 2 (a and b) respectively. It is observable from Fig 2(a) that 48.2% GMSs are associated

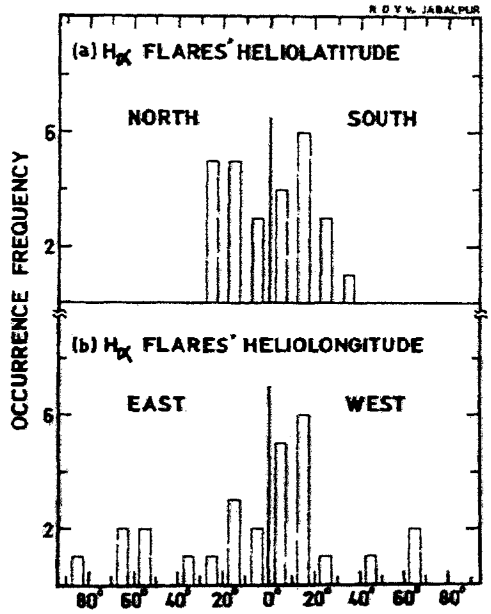

Figure 2. The occurrence frequency of the Hα solar flares with (a) Helioaltitude and (b) Heliolongitude have been plotted histographically during the period 1979-93.

with northern H_α solar flares and mostly effective latitudinal zone for producing GMSs is lying between (0-30)°N; whereas 51.8% of GMSs are associated with southern H_α solar flares and mostly effective latitudinal zone for producing GMSs is lying (0-30)°S. At the heliolatitude in the range (0-30)°N to (0-30)°S, there is concentration of 96.3% of the total H_α solar flares associated with GMSs and no storm is associated with H_α solar flares beyond 30°N and 40°S. Thus, from Fig 2(a) it is concluded that H_α solar flares have occurred within lower heliolatitude and associated with large number of GMSs. Further, it is observed from Fig. 2(b) that 44.5% of GMSs are produced by eastern H_α solar flares; whereas 55.5% GMSs are produced by western H_α solar flares. Further, 70.3% H_α solar flares are associated with GMSs at the heliolongitudinal in the range (0-40)°E to (0-40)°W. Remaining 29.7% H_α solar flares have occurred over the range (40-90)°E to (40-90)°W are associated with GMSs. Thus, it may be derived from here that the H_α solar flare have occurred within lower heliographical longitudinal zone and produce maximum number of GMSs. Occurrence frequency histogram of X-ray solar flares with different heliolatitudinal/heliolongitudinal zones associated with GMSs have been plotted in Fig. 3(a and b) for the period 1979-93 respectively. From skylab observation, it is shown that long duration soft X-ray events (LDEs) are almost always accompanied by coronal mass ejections (Sheeley et al., 1975; Kahler, 1977; Pallavicini et al., 1977). All the shocks which generate radio emission are preceded by a mass ejection. It is evident from Fig 3(a) that 54% GMSs are associated with northern X-ray solar flares and mostly effective latitudinal zone for producing GMSs is lying between (0-40)°N, 45.6% GMSs are associated with southern X-ray solar flares and mostly effective latitudinal zone for producing large number of GMS

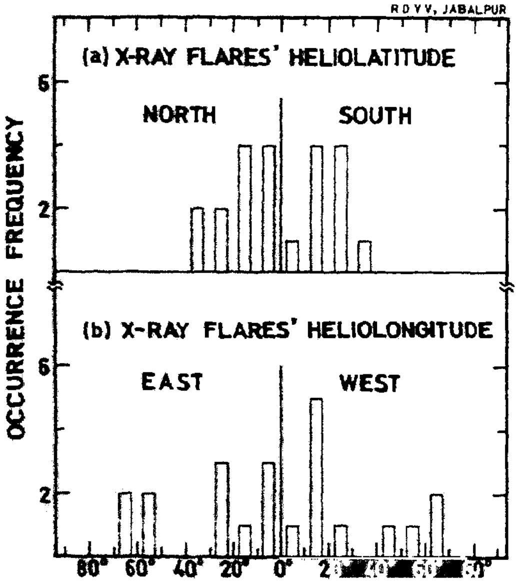

Figure 3. The occurrence frequency of X-ray solar flares with (a) Heliolatitude and (b) Heliolongitude have been plotted histographicaly during the period 1979-93.

is lying (0-40)°S. At the heliolatitude in the range (0-40)°N to (0-40)°S, there is concentration of 100% of total X-ray solar flares associated with GMSs and no storm is associated with X-ray solar flares beyond 40°N and 40°S. Further, it is evident from Fig. 3(b) that 50% GMSs are associated with each eastern and western X-ray solar flares. The mostly effective longitudinal range associated with large number of GMSs are (0-30)°E and (0-30)°W. 31.8% GMS are associated with each (0-30)°E and (0-30)°W respectively. There is concentration of 63.6% of total X-ray solar flares at the heliographical longitudinal range (0-30)°E to (0-30)°W associated with GMSs showing that large number of GMSs are associated with X-ray solar flares of lower heliographic longitude. Thus, maximum number of GMSs are associated with X-ray solar flares which have occurred within lower heliographic latitude/heliographic longitude.

A frequency occurrence histogram of APDFs with different helio-latitude/longitude associated with GMSs have been plotted in Fig. 4(a and b) for the period 1979-93. From Fig. 4(a), it is observable that 62.5% of APDFs have occurred in northern latitudinal range are associated with GMSs and mostly effective zones for producing large number of APDFs are associated with GMSs are lying between (0-30)°N; whereas, 37.5% APDFs have occurred in southern latitudinal range are associated with GMSs and mostly effective zones for producing large number of APDFs are lying between (0-30)°S. At the heliolatitude range (0-30)°N to (0-30)°S, there is concentration of 91.7% of the total APDFs are associated with GMSs. Thus, it may be inferred that APDFs have occurred within lower heliolatitude are able to produce a strong configuration of closed magnetic field region which causes fast IP shocks in interplanetary medium leading to occurrence of GMS at Earth. No storm is associated with APDFs beyond 50°N and 30°S. On higher latitude APDFs do not produce fast IP shocks and a few number of less intense GMSs are associated with these zones. Further, it is apparent from Fig 4(b) that

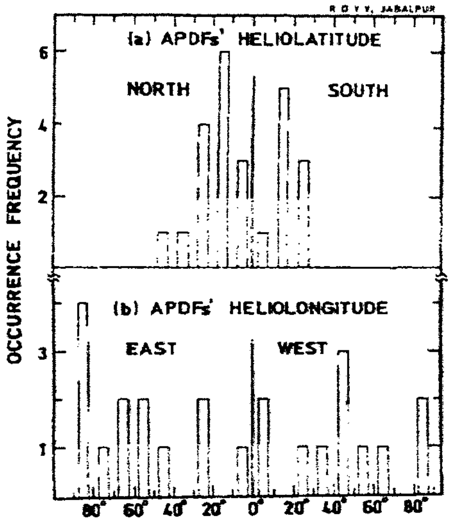

Figure 4. The occurrence frequency of APDFs with (a) Heliolatitude and (b) Heliolongitude have been plotted histographically during the period 1979-93.

54.2% of eastern APDFs are associated with GMSs and 45.8% of western APDFs are associated GMSs. A peculiar result has been obtained that 37.5% of eastern APDFs occurred at the heliolongitude range (50-90)°E of entire period only, are associated with GMSs. Furthermore, large number of eastern APDFs ie., 16.7% of eastern APDFs of entire period of consideration have occurred within heliolongitude range (80-90)°E only, are associated with GMSs. Calculations done by Hakamada and Akasofu (1982) using a kinematic model indicate that a substantial role in the propagation of geoeffective flare induced shock waves may be played by the heliospheric current sheet (HCS). Wright and McNamara (1983) found an appreciable correlation between filament activation on the Sun and the A_p index of geomagnetic activity on the ground. The geomagnetic activity during the declining phase of solar activity are related to high values of V and B. The value VB that directly modulates the geomagnetic activity. The product VB is more important for geomagnetic activity rather than IMF along (Sabbah, 2000). Association of GMSs with H_α, X-ray solar flares, APDFs and CMEs have been plotted in Venn diagram in Fig. 5 for the period 1979-93. Statistically it is found that 77.2%, 62.9 and 68.6% of S-type GMS are associated with H_α, X-ray solar flares flares and APDFs respectively. Thus we conclude that S-type GMSs are more associated with H_α solar flare than other solar features. Some previous association of GMS with solare flares by Garcia and Dryer (1987), Kumar and Yadav (2002) are consistent and by Webb (1995), Hewish and Bravo (1986) are inconsistent with our observations. Some solar flares do, infact, play a fundamental role in generating CMEs leading to cause GMSs (Breckner et al., 1998). Statistically, it is found that 92.8% and 85.7% CMEs are related to solar flares and APDFs respectively. It is observed statistically that V related to CMEs event is > 400 km/sec. 42.8% CME events are related to

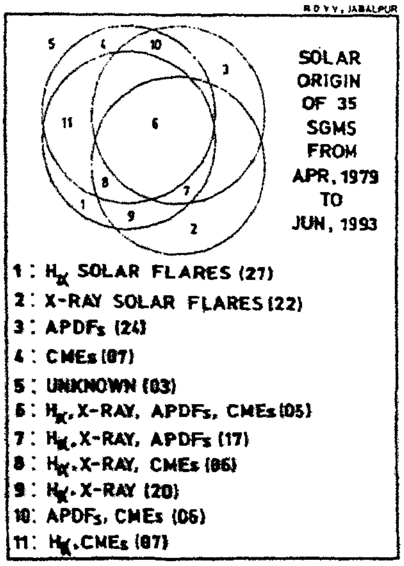

Figure 5. The solar origin of 35 severe geomagnetic storms (SGMSs) with Ap≥20 have been plotted using Venn diagram during the period Apr. 1979-Jun. 1993.

radio burst IInd and IVth. Type II, IV radio bursts are associated with flares as well as active prominences and disappearing filaments. Both CMEs driven shock and flare associated blast wave as possible causes of type II, IV radio emission. Similar result has been obtained by Kaiser et al. (1998). Thus, CMEs are related with solar flares, APDFs and radio burst type II, IV type respectively. Klassen et al. (1999) found that type IInd burst source appears in between two high soft X-ray loop system. Further, type II burst appear at different sites above the H_α flare. Thus, CMEs appear to be bright loop like structures followed by a dark cavtiy and a bright core. CMEs arise from large scale, closed magnetic field structures usually but are not always associated with other forms of solar activities such as radio burst, solar flares, eruptive prominences and disappearing filaments (EPDFs) (Kahler, 1992, Webb, 1992). Latest studies show their most commom association with eruptive prominences rather than with flares. The onset of CMEs can be associated with both flares and filaments (Feynman and Hundhausen, 1994). Recently, it is believed that the Sun generates magnetic flux tubes at the base of convection zone and transports them to the surface via the mechanism of magnetic buoyancy. A build up of magnetic flux in the corona is unavoidable unless all of the magnetic flux brought to the surface is somehow returned below the photosphere. This magnetic flux expands outward in the form of prominences and sometimes it disappears from the corona in an explosive manner. By these processes the Sun expels magnetic flux into interplanetary space and 10^{12} to 10^{13} kg of solar plasma is suddenly propelled outward into interplanetary space. Ejection speeds within 5 solar radii of the Sun's surface range from less than 50km/sec in some of the slower events to as high as 1200 km/sec in some of the faster events (Howard et al., 1985; Hundhausen et al., 1994). It is found statistically that CMEs are found in different sizes and they mostly occur at low latitudes. Similar result has been obtained by Hundhausen, 1993. Some important characteristics of CMEs (Harrison et al., 1990) are observed by satellite-borne coronagraphs. CMEs can involve the release of $10^{30} - 10^{32}$ erg. which compares 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 10km/sec to over 1000 km/sec (Rust et al., 1980; Hundhausen, 1987). The origin of these events can be clearly associated with 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. (1990). Different authors define the severeness of GMSs by taking different parameters. Garcia and Dryer, (1987) have said a storm is considered minor if $30 < A_p < 50$, major if $50 < A_p < 100$ and severe if $A_p > 100$. Gonzalez and Tsurutani (1987) consider those GMSs are intense for which $D_{st} \leq -100nT$; whereas Kohli et al. (1981) have said a storm is considered moderate if $H \leq 250$ nT, moderately severe if 250 $nT < H < 400$ nT and severe if $H > 400nT$. Thus, we can conclude that some GMSs are related to flares, active prominences and disappearing filaments and some are related to CMEs. It is found that CMEs related GMSs are not always related to HSSWS. Some CMEs are related to flares others are not. In many cases the travel time between the explosion on the Sun and maximum geomagnetic activity causing GMSs is lying between 53 to 114 Hrs. It is being evident from Fig. 5 that three GMSs are not associated with any solar features. This shows that some solar features on the back side of the solar disc are also contributing for this cause.

Conclusions

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

I. Maximum number of each H_α and X-ray solar flares with importance SF, SN are associated with large number of GMSs. No distinct correlation between magnitude of GMSs and importance of H_α, X-ray solar flares have been observed.

II. H_α, X-ray solar flares have occurred within lower heliographic latitude (0-30)°N and (0-30)°S are associated with larger number of GMSs. No H_α, X-ray solar flare have occurred beyond 40°N and 40°S in association with GMSs.

III. 91.7% of APDFs have occurred within heliolatitude range (0-30)°N and (0-30)°S are associated with GMSs.

IV. The severity and the occurrence of GMSs is also associated with different properties of H_α, X-ray solar flares and APDFs ie, NOAA region, location (helio-latitude/longitude), duration and area of solar events.

V. 77.2%, 62.8% and 68.5% of total H_α, X-ray solar flares and APDFs separately have occurred on solar surface and are associated with GMSs during the period of study.

VI. H_α, X-ray solar flares and APDF events are accompanied by coronal mass ejection. Mostly, CMEs occur at low heliolatitude.

VII. There are many occasions when erupting streams and shocks are unaccompanied by flare or filament activity anywhere on the disc (visible side).

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