CHAPTER 3
THE INFLUENCE OF CME ON GS
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3.1 Introduction

CMEs are the sources of major disturbances in interplanetary medium which further produce sudden changes in earth’s magnetic field. The major disturbances in the geomagnetosphere often persist for several days are called GSs. Thus, study of CME is very helpful to find that major features of CME which are responsible for producing GSs. It can further provide us a strong predicting parameter for GSs.

3.2 CME properties

Aschwanden (2006) stated the modern definition of CMEs as “a dynamically evolving plasma structure propagating outward from the sun into interplanetary space, carrying frozen-in magnetic flux and expanding in size”. The main parameters for CMEs identification are its geometry (position angle at the sky plane, angular width), morphology (three-part structure, flux rope), kinematics (time-distance plots, speed, acceleration), mass, kinetic energy and its magnetic properties (helicity, orientation of the magnetic field towards the earth field). When a CME travels through the corona and inner heliosphere it undergoes a multiphase kinetic evolution with varying features. The geometric and kinematic properties of CMEs are obtained from the white-light images of space-based and on-ground coronagraphs.


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3.2.1 Morphology

CMEs classified according to their morphology in three ways- three part structured CMEs, Narrow CMEs and CMEs with clear flux-rope morphology (Howard et al., 1985). Generally, CMEs appear as a “three-part” structure comprised of a brighter core underlying a darker cavity embedded in outer bright front, shown in Fig. 3.1 (Hundhausen, 1987). This is considered to be the standard morphology for CMEs.

![Figure 3.1](image)

**Figure 3.1:** A standard model for a “three-part” CME: a prominence and its surrounding cavity rise through the lower corona, followed by sequential magnetic reconnection and the formation of flare ribbons at the footpoint of a loop arcade (Forbes, 2000).

Mostly, the core of CME is identified as prominence material having helical structure. The outer front may contain primary swept-up material (Illing & Hundhausen, 1985) and the cavity is lower plasma density region with higher magnetic field strength. The narrow CMEs show jet-like motions probably along open magnetic field, whereas normal CMEs are characterized by a closed frontal loop.
Figure 3.2: CME represents “three part structure” morphology (left) and “flux rope” morphology (right).

3.2.2 Mass and Energy

The mass of a CME can be estimated based on the Thomson-scattering formulae (Hundhausen, 1993). It is often assumed that the CME is close to the plane of the sky without the knowledge of the exact position of the density-enhanced structure. Thus, there is a possibility of large number of uncertainty in estimation of CME mass because it involves number of assumptions. Especially for halo events, the mass of the CME underestimated. The mass of CME at the distances $R > 2$ solar radii may be
obtained from the data of coronagraphic white-light measurements with corrections depending on the geometry of eruption (Vourlidas et al., 2000; Vourlidas & Howard, 2006). Typically, the mass of a CME falls in the range of $1 \times 10^{11} - 4 \times 10^{13}$ kg, averaged at $3 \times 10^{12}$ kg (Gopalswamy & Kundu, 1992).

Table 3.1: The average properties of CMEs from different sources.

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</thead>
<tbody>
<tr>
<td></td>
<td>Angular Size (deg)</td>
<td>37</td>
<td>47</td>
<td>42</td>
<td>43</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Speed (km/s)</td>
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<td>349</td>
<td>470</td>
<td>460</td>
<td>424</td>
</tr>
<tr>
<td></td>
<td>Mass (g)</td>
<td>$3.3 \times 10^{15}$</td>
<td>$4.7 \times 10^{15}$</td>
<td>$4.0 \times 10^{15}$</td>
<td>$1.7 \times 10^{15}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K.E (erg)</td>
<td>$6.7 \times 10^{30}$</td>
<td>$3.1 \times 10^{30}$</td>
<td>$3.4 \times 10^{30}$</td>
<td>$4.3 \times 10^{30}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P.E (erg)</td>
<td>$7.1 \times 10^{30}$</td>
<td>$8.0 \times 10^{30}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$St. Cyr et al. (1999).
$^b$Hundhausen (1993).
$^c$Gosling et al. (1976), Rust (1979) and Hundhausen (1993).
$^d$Howard et al. (1985) and Howard et al. (1986).
$^e$St. Cyr et al. (2000) and Vourlidas et al. (2002).

It is found that the kinetic and potential energies of a typical CME amount to $10^{22} - 10^{25}$ J (Vourlidas et al., 2000; Emslie et al., 2004). Schwenn et al. (2006) found in his study of all CMEs from 1996 to December, 2004 that the maximum kinetic energy of CMEs is $10^{12} - 10^{13}$ erg. Also, the “average CME” has mass of $1.4 \times 10^{15}$ g and kinetic energy of $2.6 \times 10^{30}$ erg.

Some very fast and wide CMEs generally originating from large active regions and accompanied by powerful flares can have kinetic energies exceeding $10^{33}$ erg (Gopalswamy et al., 2005a). The average values of some observational properties, estimated by different authors are categorized in Table 3.1.

3.2.3 CME Rate

Generally CME occurs during solar maximum with a relatively high rate. Its rate increases from one every day around solar minimum to more than 6 per day during
solar maximum. GSs occur within 5 days after the onset of CMEs (Prasad, Garia & Bhatt, 2013)

3.2.4 Angular width

The angular width of CMEs ranges from $2^\circ$ to $360^\circ$, projected in the plane of the sky (Yashiro et al., 2004). The angular widths of narrow CMEs are less than $10^\circ$ (Wang et al., 1998). The width of a CME occurring close to the limb is the true width whereas for a CME occurring close to the disk center, width is affected by projection effects (Burkepile et al., 2004). Full halo CME has an apparent width ($W$) of $360^0$, while partial-halo CME has $120^0 \leq W < 360^0$. Halo CMEs have special properties due to projection effect (Burkepile et al., 2004). Halo CMEs, first discovered by Howard et al. (1982), appear with a full and partial circular shape surrounding the sun and presumably have a component moving along the sun-earth line. Full halo CME has an apparent width of $360^0$, while partial-halo CME has $120^0 \leq W < 360^0$. Halos with their sources within $\pm 45^0$ of the Central Meridian Distance (CMD) are known as disk halos, while those with central meridian beyond $\pm 45^0$ but not beyond $\pm 90^0$ are known as limb halos. A halo CME if initiated on the front side of the solar disk (front sided halo CME) can move towards the earth or away if initiated on the backside (St. Cyr et al., 2000). We found in our investigation that halo CMEs are more geoeffective than non halo CMEs and the fast halo CMEs having low Travel Time (TT) are more geoeffective (Prasad, Garia & Bhatt, 2013).

3.2.5 CME Speed

The initial speed of a CME is usually measured by constructing a height- time diagram. The height time plots of a CME is drawn by identifying the leading edge of the CME (CME front as it appears projected on plane of the sky) on the sequence of white light images recorded at regular time interval of the FOV of coronograph. Inevitably, the plane of sky values can deviate from the real radial speed of the CME front, depending on the actual direction of the motion. The straight line fit to the ‘height time data’ yields the linear speed and the second order fit provides the radial speed profile and an effective acceleration of CMEs. The FOV of LASCO
coronagraph extends up to a heliocentric radius of \( R \approx 30 \) solar radii where the white light images of this FOV are recorded at regular time intervals. The speed we obtain from LASCO data is sky–plane speed not the space speed because the propagation of CME is effected by solar activity, drag force due to momentum change between CMEs and ambient mediums and by the presence of preceding CMEs. We found a significant correlation coefficient between CME linear speed and Dst for southern event about -0.59 (Table 3.5). Thus, linear speed found to be more useful parameter for predicting the occurrence of major GSs for the southern halo CMEs than northern halo CMEs whereas CME acceleration does not appear to be a very reliable predictor for the resulting storm intensity (Prasad, Garia & Bhatt, 2013).

### 3.2.6 Acceleration

CMEs speed up, move with constant speed or speed down represent that CMEs usually undergoes a multiphase kinetic evolution, with a acceleration of a CME positive in the inner corona, close to zero or negative values in the outer corona respectively. There are small positive accelerations for slower events and small negative accelerations for faster events (Vrsnak et al., 2004). Wen et al. (2008) verify that slower CMEs tend to have the positive acceleration at above 5 solar radii while less than 10% faster CMEs represented as average negative acceleration (about 2.2 \( \text{m/s}^2 \)) as they propagate from 5 to 30 solar radii.

### 3.2.7 Physical Properties of CMEs

CMEs physically characterized by its density, temperature, magnetic field, elemental composition and ionization state. The density of CMEs measured by using white light images (electron column density integrated along the line of sight in different part of CMEs), radio observation of thermal emission and the ratio of collisionally and radiatively excited components of a UV spectral line. The white-light densities are generally of the order of \( 10^4 \text{–} 10^5 \text{ cm}^{-3} \) for middle corona heights (4 to 7 solar radii). The optically thick CME plasma has densities above \( 7 \times 10^8 \text{ cm}^{-3} \) at 1.3 solar radii and temperature \( 10^4 \text{ K} \) (Akmal et al., 2001).
The basic composition of CME material is coronal plasma may have altered charge state. Raymond et al. (2003) detected a spectral line in various CMEs and stated the presence of species from H I and C II to [Fe XVIII] and [Fe XXI]. Further, the presence of little cool plasma, but the high temperature ions [Fe XVIII], [Fe XX] and [Fe XXI] in the more powerful and faster CMEs, are also considered.

The magnetic field in CMEs is measured by the analysis of gyroresonance emission, of polarization spectra of the thermal emission and of gyrocinchrotron emission. The strength of magnetic field is 3–30 G in quiescent prominences and 20–70 G in active prominences (Tandberg-Hanssen, 1995).

### 3.3 Propagation of CME in Solar Wind

The CME plasma is entrained in the Interplanetary Magnetic Field (IMF) lines and is transported in solar wind. The solar wind speed is usually much larger than the local sound speed or Alfvén speed. We analyzed 11 year (1997-2008) GSs with wind and IMF parameter and found that the plasma flow pressure (solar wind pressure) is maximum one day before the GSs whereas solar wind speed is maximum during the GSs. Thus, the enhancement of plasma flow pressure is followed by enhanced solar wind speed near the earth and this enhanced solar wind speed (>440 km/s) mostly occurs during time of GSs (Prasad, Garia & Bhatt, 2013).

#### 3.3.1 Interplanetary Magnetic Field (IMF)

IMF is a part of sun’s magnetic field that is carried into interplanetary space by the solar wind. The solar wind stretches the radial field of sun into spiral field lines with an azimuthal field component. Thus, the resulting Archimedian spiral (Parker spiral) geometry of IMF, which leave the sun near-vertically to the surface and cross the earth orbital at an angle of about 45° (Parker, 1963b). This basic geometry of IMF based on four assumptions: (i) the solar wind moves radially away from sun at a constant speed; (ii) the sun rotates with constant period (with a synodic period of 27.27 days at prime meridian defined by Carrington); (iii) the solar wind is azimuthally symmetric with respect to solar rotational axis; and (iv) the IMF is frozen-in solar wind and anchored at the surface of sun.
The Parker’s spiral is waves as a “Ballerina skirt” due to existence of the angle $7^\circ$ between solar magnetic and rotation axis (Fig. 3.3). The strength of IMF depends on solar cycle, varying between $B \approx 6nT$ and $9nT$ at a distance of 1AU. The IMF is a vector quantity with three directional components $B_x$, $B_y$ and $B_z$. The $B_x$ and $B_y$ components are parallel to ecliptic plane and the third component $B_z$ is perpendicular to ecliptic plane created by waves and other disturbances in solar wind. Our investigation states that

**Figure 3.3:** The solar Ballerina model- the rotating sun with a wrapped Haliospheric Current Sheet (HCS) dances across the earth.

Plasma flow pressure together with solar wind speed near the earth is a geo-effective parameter, when IMF $B_z$ component is southward (Prasad, Garia & Bhatt, 2013). Thus, $B_z$ is a very important parameter to trigger the GSs. The IMF can be heavily disturbed by CME-related shocks and propagating CMEs. The CME plasma is entrained in the IMF lines and is transported in solar wind. Typically, solar wind having a Mach number of $\approx 10$, which implies that, the dynamic pressure is much higher than both the magnetic pressure and the thermal pressure. The high conductivity of solar wind flow creates a frozen-in magnetic field in solar wind.
3.3.2 Interplanetary Coronal Mass Ejections (ICMEs)

CMEs are responsible to create disturbances in solar wind. Various signatures of CMEs in the solar wind includes: (i) transient interplanetary shock waves, (ii) Helium (He) abundance enhancements, (iii) unusual ionization states (e.g., He+), (iv) brief density enhancements and long duration density decreases, (v) proton and electron temperature depressions, (vi) bi-directional field aligned flow of halo electrons and low energy protons, and (vii) magnetic field variations associated with flux ropes. The ICMEs are interplanetary manifestation of CMEs (Fig. 3.4).

ICMEs are classified as Magnetic Cloud (MC) and Non Magnetic cloud (NMC). The ICMEs contains ordered magnetic field, magnetic field strength higher than the average, smoothly rotating magnetic field direction through large angle and low proton temperature are called MC (Gosling, 1990). MCs are force free magnetic field configuration.

Figure 3.4: The Schematic three-dimensional structure of an ICME and upstream shock, relating magnetic field and plasma signatures.

Fig. 3.4 represents that ICME follow shock and sheath region which is very effective region to cause FDs in cosmic rays and GSs. We found that fast ICMEs are geo-effective more than slower ICMEs whereas slow ICMEs are Cosmic ray effective (Prasad, Garia & Bhatt, 2013).
When CMEs propagate in interplanetary space, there are a number of complications that can occur, such as a faster CME can catch up with slower CME and interact. Such interactions form compound streams in the inner heliosphere. These systems continuously evolve further and merge with other CMEs and shocks when they move outward. In the outer heliosphere (beyond 10 - 15 AU), such structures form and are termed as merged interaction regions, which become so extensive that they encircle the sun like a distant belt. Such regions are responsible to block and modulate Galactic Cosmic Rays (GCR).

### 3.3.3 Shocks

CMEs have typical propagation speed of $v \approx 300 - 400$ km/s. But fast CMEs speed has been measured more than 2000 km/s. Thus, such fast CMEs (super Alfvénic) can drive transient interplanetary shocks. The driving plasma of the transient shock is typically cold (indicating a CME origin) and it is sometimes enriched in fully ionized Helium. As the front of fast CME overtake the slower solar wind, a strong gradient develops and pressure wave steepen into a forward shock propagating into an ambient wind ahead, occasionally a reverse shock propagates back through the CME towards the sun. The fast forward shock was identified by the sudden increase of the IMF intensity, the Solar Wind Pressure (SWP) bulk speed density and temperature in near earth space solar wind data at the time of Sudden Commencement (SC).

### 3.3.4 Sheath

Behind the shock a discontinuity is formed between a compressed ambient plasma and material of driving plasma. The sheath material is slow solar wind that has been swept by the ICME but not a part of ICME itself. The sufficiently turbulent field in sheath region between shock front and magnetic clouds is indicated by large variation in both field strength and direction. The magnetic field in ICME sheath is turbulent (fluctuation in the magnetic field and plasma velocity and density) and contains tangential discontinuity (large numbers of sharp changes in magnetic field directions, having no magnetic field threading through the plane of structure). This turbulence in sheath region is an important factor causing FD in cosmic ray intensity. The
discontinuities dramatically reduce particle diffusion and make sheath region effective in causing FDs in cosmic rays.

3.4 Interaction of Solar Wind with Earth’s Magnetosphere

The interaction between interplanetary plasma and Magnetic field (solar wind, IMF) and geomagnetic field shapes the region above the ionosphere called the earth’s magnetosphere. It is formed as a cavity in solar wind where dayside field lines being compressed and night side field lines are drawn out into a comet like tail (Fig. 3.5). When intense solar wind reaches near earth, the dayside of magnetosphere is compressed to distance approximately 10 earth radii. Since the solar wind expands at speeds exceeding the fast magnetosonic speed, a bow shock is generated surrounding the magnetosphere. The shocked solar wind flowing around the magnetosphere outside the magnetopause forms the magnetosheath. The magnetopause is a two-dimensional surface which perfectly shields the magnetospheric magnetic field from the IMF. However, the interconnection between the two regions across the magnetopause is a crucial consequence of solar wind–magnetosphere interaction involving reconnection. This provides a path for solar wind particles to enter earth’s magnetosphere (Cluster observes a 'porous' magnetopause", 2012).

The magnetosphere is filled with tenuous plasma of different density and temperature which originates with solar wind and ionosphere. The magnetic field of sun and earth coupled by magnetic reconnection at the front side (dayside) of the magnetosphere when the interplanetary Bz turns south, i.e. antiparallel to the earth’s intrinsic field. This process allows charged particles to penetrate from outer space and way down into earth’s magnetosphere through the polar cusps along the geomagnetic lines. Polar cusps are the regions where the field lines split. The magnetic field lines from high latitude splits on the dayside, some crossing the equator while other crossing the polar cusps. The positive ions and electron follow magnetic field lines but in opposite directions and form field aligned current (Fig. 3.7). Some of the solar wind particles move along magnetotail and other particle are accelerated into high latitude ionosphere, collides with the molecules of ionosphere and form an oval of light (Fig. 3.6) around the polar regions of earth, called auroral ovals. The northern ovals of
light are called **aurora borealis** and in southern region it is known as **aurora australis**.

![Diagram of Earth's magnetosphere](image)

**Figure 3.5:** Schematic illustration of earth’s magnetosphere with different plasma regions (Space environments and effects program NASA, Marshall Space Flight Centre, [http://see.msfc.nasa.gov/](http://see.msfc.nasa.gov/)).

![Aurora display](image)

**Figure 3.6:** The auroral display over the EISCAT, UHF antenna in Sodankyl, Finland.
Magnetic reconnection in the tail causes ejection of plasmoids away from the earth and injection of plasma lobe into the polar cusps. On the night side the magnetic field is drawn out into a long tail consist of two lobes separated by a thick sheet of particles called plasmasheet, where most of the magnetotail plasma is concentrated. The plasma sheet reaches the high-latitude ionosphere near the earth. The outer region of the magnetotail is called the magnetotail lobe, which contains highly rarefied plasma. The plasmasphere (inner magnetosphere) consists of particles of low energy (usually less than 1 eV) and relatively high density (10-10^3 cm^-3) plasma component on the closed nearly bipolar geomagnetic field lines at low and mid-latitudes. This population decreases outwards and terminates at a boundary called the plasmapause, which is usually relatively sharp.

The highly energetic particles trapped by geomagnetic field forced to undergo azimuthal drift due to gradient and curvature of magnetic field in earth’s inner magnetosphere form radiation belt known as Van Allen radiation belts. These radiation belts mainly consist of protons and electrons with energies between ~ 40 keV and a few hundred MeV. The protons of inner belt are highly energetic in comparison to outer belt. The outer Ven Allen radiation belt contains charged particles are mainly electron of both atmospheric and solar origins. The most energetic particles of outer belt are electrons.

3.4.1 Ring Current
The terrestrial ring current is a ring of westward electric current created by energetic charged particle flowing around the earth at equatorial plane and extending from 2 to 9 earth radii. The ring current is produced by the drift of charged particles of outer Ven Allen radiation belt around the earth. Although particles of almost all energies contribute to the ring current, but the name ring current particles is typically applied to particles with medium energy range 10 - 200 keV.
Ring current consist of fully ionized particles that are trapped orbits about the earth and have sufficient energy to carry substantial current. Here the energetic particles tend to behave independently rather than as a part of a fluid. It was found that the direction of the $B_z$ component of the IMF regulates the growth and decay of the ring current. The ring current becomes very intense during GSs. The particles of ring current (radiation belt) undergo three types of motion-cyclotron motion, a bounce motion along field lines between mirror points and a drift motion around magnetic field axis. The ring current is responsible for decrease in earth’s surface magnetic field.

### 3.4.2 Geomagnetic Storms (GSs)

GSs are temporary disturbances in geomagnetosphere. When intense solar wind reaches earth, the dayside of magnetosphere is compressed closer to the surface of earth and the geomagnetic field fluctuates widely. This type of event generally called a GS. During GSs the magnetic field at earth surface is perturbed by the strong electric currents flowing within both magnetosphere and ionosphere, the aurora...
brightens and extends to low magnetic latitudes and intense fluxes of energetic charged particles are generated within magnetosphere. An ideal GS has four phases - Sudden Commencement (SC), an initial phase, a main phase and a recovery phase (Fig. 3.8). This picture of the storm involved a sudden positive increase in the H component (SC) followed by a period of arbitrary length in which the elevated field does not change significantly: the initial phase. The SC is the effect of a compression of the front side of the magnetosphere by enhanced solar wind pressure. Some storms have no SC. Some storms have a SC but no initial phase. In that case, the main phase begins immediately just after the compression.

![Diagram](image)

**Figure 3.8:** Four phases of an ideal GS- SC, initial phase, main phase and recovery phase.

In main phase of a GS (Dst ≤ -50 nT), The depression of the magnetic field during the main phase was the effect of a ring current carried primarily by energetic ions. The minimum value during a storm will be between -50 and approximately -600 nT. The main phase represents ring current injection, which results from a southward IMF and the resultant strong convection. The recovery phase is the period when Dst changes from its minimum value to its quiet time value. The period of the recovery phase may be as short as 8 hours or as long as 7 days. The recovery phase is due to loss of ring-current ions as a result of charge exchange with the neutral exosphere. We use geomagnetic indices to monitor the geomagnetic activity on a global scale, which is related to solar activity. These geomagnetic indexes are Dst, Kp, aa, ap, AL, AU, and AE. The Kp measurers the rate of change of magnetic field near the earth. It is used to
determine ap index (mean amplitude of magnetic activity). AE index is used to indicate the strength of the electrojet measure from high latitude stations. Among all the geomagnetic indices, we choose Dst to measure geomagnetic activity because the Dst is the conventional measure of ring current intensity and energy observed at earth's surface over low and moderate latitudes. It is the best indicator of ring current intensity and a very sensitive index to measure the degree of solar wind disturbances.

3.4.2.1 Disturbance storm time (Dst) index

The principal property of a GS is the creation of an enhanced ring current. The growth of the ring current begins with the so-called injection of particles into the inner magnetosphere from the magnetotail. Dst is a measure of the deviation of H (northward) component of the magnetic field near the earth’s equator lasting normally over one to several days. This deviation is caused by the ring current flowing westward in the magnetosphere and can be monitored by the Dst index. Dst index has been introduced by Sugiura (1991) is the conventional measure of ring current intensity and energy. It is derived from the instantaneous longitudinal average of the mid-latitude magnetic disturbances.

3.4.3 Effect of GS

The strong coupling of solar wind and earth’s magnetosphere causes various changes in magnetosphere during GSs. The high latitude currents which occur in the ionosphere changes rapidly produce their own magnetic field which combines with earth’s magnetic field. Most of our communication systems (TV/Radio broadcast, Long-distance telephone service, Cell phones, Pagers, Internet and Finance transactions) are satellite based and utilize the ionosphere to reflect radio signals over long distances. The altered ionosphere often create distorted and completely fade out reflected communications.

During time of higher solar activity there is an increase in ultra violet radiation and auroral energy input, this heat up earth’s atmosphere, causing it to expand. The low orbiting satellites then encounter increased fractional drag which causes them to drop
in there orbits. However, satellites with propulsion system again rose back to correct orbits but in some satellites, orbit decay cause them to fall to earth. The impact of high speed particles has a corrosive effect on the high altitude satellites, in geosynchronous orbits satellites, and charge built up can result from these particles. Electrical discharges can arc across spacecraft component and cause damage.

When the ionosphere between the satellites and the user becomes turbulent and irregular, the signal may “scintillate” and prove difficult to track. Thus, loss of signal lock on one or several satellites and both single and dual frequency systems may be affected. For example the GS (Bastille event) of 14-16 July, 2000 with Dst = -300 nT cause following effects:

ASCA (Advanced Satellite for Cosmology and Astrophysics) – lost attitude fix resulting in solar array misalignment and power loss.
GOES-8 & GOES-10 – SEM electron sensor problems (power panels).
ACE – Temporary solar wind and other sensor problems.
Wind – Permanent (25%) loss of primary transmitter power & temporary loss of sun and star sensors.
SOHO (also Yohkoh & TRACE) – High energy protons obscure solar imagery. A number of military systems radar and submarine detection are greatly hampered during times of solar activity. Jamming of air traffic control frequencies are dangerous situation for air traveler.

At ground level, Geomagnetically Induce Current (GIC) is produced as the result of changing magnetic field. This direct current leak out through all long conductors (power grids, oil and gas pipelines). Induced current are much more serious at high latitudes near the auroral oval and in areas which lie above large deposits of igneous rock. In pipelines these induced current cause increased corrosions and malfunctions of flow meters. In large power systems, surges of induced current overload transformers and capacitor banks, causing damage and shut down. Thus, major GSs may cause damage to high voltage lines in arctic regions, anomalous corrosion of oil pipelines in arctic regions and malfunction of magnetic compasses.
Figure 3.9: Solar-terrestrial effects on ground and space-based technologies.

GSs cause biological effects also. The geomagnetic activity disturbances influence on the human cardiovascular state through variations of heart rate (HR), arterial diastolic and systolic blood pressure (Dimitrova et al., 2009). It affects the central and vegetative nervous system through changes of the human brain’s functional state and the psycho-emotional state (Babayev & Allahverdiyeva, 2007). It was shown that very low geomagnetic activity could also affect also adversely human cardio-vascular system (Stoupel et al., 2007). Since the above effect are solar generated and occurs generally when CME in solar wind travels near the earth so the study of CME provides us space weather warning features. This space weather warning will be very important for our society in the future.

3.5 Method of analysis

We analyzed the data by using correlation method of statistical analysis and Chree analysis by superposed epoch method.
3.5.1 Correlation coefficient

Correlation coefficient is measurement of strength of relationship between two random variables numerically. The most familiar correlation coefficient is the Pearson product-moment correlation coefficient, or "Pearson's correlation coefficient". It is obtained by dividing the covariance of the two variables by the product of their individual standard deviations. The equation for the correlation coefficient is

$$r = \text{Correl}(x, y) = \frac{\Sigma(x-x)(y-y)}{\sqrt{\Sigma(x-x)^2}\sqrt{\Sigma(y-y)^2}} \quad \text{...3.1}$$

Where $\bar{x}$ and $\bar{y}$ are the sample means of $x$ and $y$. The Pearson correlation is defined only if both of the standard deviations are non zero and finite. It has value between $-1$ and $+1$(where $1$ in absolute value ) indicating the degree of linear dependence between the variables. The closer the coefficient is to be either $-1$ or $+1$, the stronger the correlation between the variables. The Pearson correlation is $+1$ in the case of a perfect direct (increasing) linear relationship (correlation), $-1$ in the case of a perfect decreasing (inverse) linear relationship (anticorrelation), and if the variables are independent, Pearson's correlation coefficient is 0. The correlation coefficient is symmetric: $\text{corr}(x,y) = \text{corr}(y,x)$.

The strength of Correlation coefficients can be classified as-

When $0.9 < |r| < 1$, indicates that the variables are very highly correlated.

When $0.7 < |r| < 0.9$ then the two variables are highly correlated.

The two variables are moderately correlated when value of correlation coefficient lies between 0.5 to 0.7 and when $0.3 < |r| < 0.5$ then there is a low class correlation between two variables.

We are explaining the method in following steps to find the correlation coefficient between $x$ and $y$ variables given in Table 3.2.

Table 3.2: It represents the values of two variables $x$ and $y$ to calculate correlation coefficient.

<table>
<thead>
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<th>X</th>
<th>6</th>
<th>4.9</th>
<th>3.5</th>
<th>4.6</th>
<th>5.5</th>
<th>5.4</th>
<th>6.5</th>
<th>4.5</th>
<th>3.4</th>
<th>12.9</th>
<th>10.2</th>
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<tbody>
<tr>
<td>Y</td>
<td>1.3</td>
<td>0.6</td>
<td>-0.2</td>
<td>-0.5</td>
<td>1.1</td>
<td>1.6</td>
<td>-1.3</td>
<td>-0.1</td>
<td>-0.6</td>
<td>-3.4</td>
<td>4.3</td>
</tr>
</tbody>
</table>
Step 2: find \((x - \bar{x}), (y - \bar{y}), (x - \bar{x})(y - \bar{y}), (x - \bar{x})^2, (y - \bar{y})^2\)

Table 3.2.1: Tabular form of all necessary calculated values related to variables \(x\) and \(y\) to find correlation coefficient.

<table>
<thead>
<tr>
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Step 3: Calculate \(\sum (x - \bar{x})(y - \bar{y}), \sum (x - \bar{x})^2, \sum (y - \bar{y})^2\)

We find

\[
\sum (x - \bar{x})(y - \bar{y}) = -5.66635, \quad \sum (x - \bar{x})^2 = 84.36175, \quad \sum (y - \bar{y})^2 = 37.50735
\]

Step 4. Calculate correlation coefficient

\[
r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}
\]

\[
r = \frac{-5.66635}{\sqrt{84.36175 \times 37.50735}}
\]

\[
r = -0.1007
\]

Result: There is a very poor negative correlation between \(x\) and \(y\). They are about independent events (quantity).
3.5.1.1 Study of Halo CMEs in Association with GSs during 1999-2005

Halo CMEs are fast and wide events on the average. They are associated with flare of greater X-ray importance. Halo CMEs are the energetic events and presumably the source of major GSs. Halo CMEs with average speed 1000 km/s are more energetic compared to ordinary CMEs with average speed 470 km/s, hence the speed of a CME impact earth’s magnetosphere of energetic halo CMEs to be higher than ordinary CMEs. The shocks driven by halo CMEs are frequently responsible for driving large GSs (e.g., Gopalswamy, Yashiro & Akiyama, 2007). Thus, we choose halo CMEs to find the features of CMEs that are responsible to create GSs.

In our study GSs are classified as: super-intense storm (Dst ≤ -200 nT), intense storm (-200 nT < Dst ≤ -100 nT) and moderate storm (-100 nT < Dst ≤ -50 nT) as taken by Srivastava et al. (2004).

3.5.1.2 Data and Identification Method

In the present investigation, halo CMEs of 6 years which have been catalogued on website (http://cdaw.gsfc.nasa.gov/CME_list) are taken into account for the study. In the 6 year period from 1 January, 2000 to 31 December, 2005 about 7779 CMEs are observed by LASCO among them 298 CMEs (or 3.8%) are halos and 588 CMEs (or 7.5%) are partial halos.

The selected list of 67 halo CMEs with their complete features from 2000 to 2005 are given in Table 3.3. Some of the halo CME events may not be occurred during data gap in LASCO observation because during that period the SOHO spacecraft went into non functional mode. The first column represents the date and time measured when a halo CME first appeared in the LASCO’s FOV. The second and third columns of table are from the SOHO/LASCO catalogue represents linear speed and acceleration. For each CME, the source co-ordinates (fourth column, Table 3.3) of the associated flare and filament activities on sun has identified with the help of Dst plots (Fig. 3.10) in SOHO/LASCO catalogue and flare list provided by the Solar Geophysical Data
The fifth column of table represent Dst index for GSs. To identify Dst index of selected halo CMEs we make use of Dst plots (see Fig. 3.10) from SOHO/LASCO catalogue. It is clear from the figure that a halo CME of 29 May, 2003 (01:27 UT) having source co-ordinate is S06 W37 is responsible for nearby intense GS (- 135 nT) of 30 May, 2003 (02:00 UT). We also refer to an updated version of the “comprehensive” ICME list compiled by Cane and Richardson (2003, 2008) for the values of Dst index of selected halo CMEs. The solar source of eruption also identified from Javascript movies (e.g. see Fig. 3.11) from SOHO/LASCO CME catalogue. This figure shows that CME of 29 May, 2003 located in the western hemisphere of the sun is associated with X1.2 flare. The last column of Table 3.3 represents TT of the CME. The $TT = T^{ICME} - T^{HCME}$, was obtained from the difference in the time of first appearance of a given halo CME in the LASCO coronagraph ($T^{HCME}$) and the respective ICME in Wind observations ($T^{ICME}$) (Michalek et al., 2004). The time of initiation of CME ($T^{CME}$) is shown in first column (Table 3.3) and the time of arrival of ICME ($T^{ICME}$) at the wind spacecraft is obtained from Richardson and Cane ICME list (2003, 2008).

Table 3.3: List of 67 halo CMEs and their features from 2000-2005.

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<th>S.No</th>
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<th>Flare</th>
<th>Source co-ordinates</th>
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Figure 3.10: Dst plot for 29 May, 2003 CME event: (top) Dst index plots, (middle) CME height-time plots and (bottom) GOES soft X-ray light curve (see SOHO/LASCO catalog http://cdaw.gsfc.nasa.gov/CME_list/daily_plots/dsthtx_2003_05/dsthtx_20030529.html)

Figure 3.11: One frame of a JavaScript movie combining the LASCO C2 images (left) with the GOES soft X-ray light curve (right). It is showing the disturbance in the southwest quadrant of the sun. The vertical line in the GOES plot marks the time of the LASCO image (event of 29 May, 2003). (http://cdaw.gsfc.nasa.gov/movie/make_javamovie.php?stime=20030528_2355&etime=20030529_0351&img1=lasc2rdf&title=<h2>20030529.012712.p260g).
Figure 3.12: Bar diagram representing number of halo CMEs vs. year for the period of 2000-2005.

Figure 3.13: The number of halo CMEs in different TT intervals (hrs) for period 2000-2005.
Table 3.4: Geo-effectiveness of halo CMEs in different TT intervals for the period 2000-2005.

<table>
<thead>
<tr>
<th>GS</th>
<th>No. of halo CMEs having TT interval 20-40hrs and average speed 1595 km/s (%)</th>
<th>No. of halo CMEs having TT interval 40-60 hrs and average linear speed 1158.3 km/s (%)</th>
<th>No. of halo CMEs having TT interval 60-80 hrs and average linear speed 785.5 km/s (%)</th>
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</thead>
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<tr>
<td>Super-intense Storm</td>
<td>43%</td>
<td>2%</td>
<td>16%</td>
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<td>Intense Storm</td>
<td>57%</td>
<td>53%</td>
<td>47%</td>
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Table 3.5: Correlation coefficients of CME features with Dst index and TT of CMEs.

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<th>The variables</th>
<th>Correlation Coefficient</th>
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<td>CME linear speed-Dst</td>
<td>-0.35 (for southern events -0.55)</td>
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<td>CME acceleration-Dst</td>
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<td>CME linear speed-TT</td>
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<td>CME acceleration-TT</td>
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Table 3.6: Geo-effectiveness of halo CMEs associated with different class of solar Flares.

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<th>Geomagnetic Storm occurrence in different Flare Class</th>
<th>Flare Class</th>
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<tr>
<td>3% (Intense) 0% (Super intense)</td>
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<tr>
<td>30% (Intense) 13% (Super intense)</td>
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<td>27% (Intense) 33% (Super intense)</td>
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<tr>
<td>37% (Intense) 53% (Super intense)</td>
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</table>
3.5.1.3 Results and Discussion

The statistical analyses of our results are summarized in the form of bar charts and tables.

(i) The number of halo CMEs for the year 2001 is maximum (63) then decreasing to minimum (31) in 2003 and again rising slowly to 55 in 2005 (see Fig. 3.12). Since the maximum numbers of halo CMEs have occurred during the solar maximum year 2001. So the population of occurrence of halo CMEs generally follows the phase of solar cycle. In figure the peak occurrence of halo CME rate (during 2001) is delayed by about one year when compared to the SunSpot Numbers (SSNs) that peaked during the year 2000. Gopalswamy et al. (2003a) have indicated that the peak occurrence of CME rate (during 2002) is delayed by about two years when compared to the SSNs that peaked during the year 2000.

(ii) We have plotted the number of events (No. of halo CMEs) with different TT intervals (Fig. 3.13). The numbers of halos with TT in interval 40-60 hrs are maximum 30. Similarly 19 halos and 14 halos belong to TT in intervals 60-80 hrs and 20-40 hrs respectively. Then we have calculated the average linear speed (Arithmetic Mean) of all halo CMEs belonging to different TT intervals. Here we have neglected the value of lower and upper limit of TT intervals 0 - 20 hrs and 80 -100 hrs because of their negotiable numbers. The number of halo CMEs out of these 30 having TT in interval 40- 60 hrs and average linear speed 1595 km/s responsible for creating intense and super-intense GSs are calculated in percentage (Table 3.4). Similarly, we have calculated these values for TT intervals 20- 40 hrs and 60-80 hrs. It is clear from the table that intense and super-intense GSs are respectively caused by 53% and 2% of halo CMEs with TT in interval 40-60 hrs and the average linear speed 1158.3 km/s. About 47% of halo CMEs with TT in interval 60-80 hrs and the average linear speed 785.5 km/s are responsible for intense storm and 16% are responsible for super-intense storm. Also, intense and super-intense GSs are respectively caused by 57% and 43% of halo CMEs having TT in interval 20-40 hrs and average linear speed 1595 km/s. Thus, the result shows that halo CMEs having high average linear speed and low TT are strong candidates for creating major GSs.
The event of 29 October, 2003 (20:54 UT) has a high linear speed of 2029 km/s and low TT (≈19 hrs) is responsible for super-intense GS with Dst index -383 nT. This event is result of the sporadic phenomena in the AR 486 and was observed after extremely powerful X-ray flare X10.0 on 29 October. A very fast halo CME accompanied the flare and it was first observed in the LASCO C2 field of view at 20:54 UT as a moderately bright loop front over the south west limb. This CME, too, consisted of a faint halo front and a bright dense core. The mean plane of sky speed of the halo CME, measured at Position Angle (PA) =190° where the leading edge moved fastest, was about 2029 km/s, while the mean speed of the bright core was considerably smaller and measured at about 1400 km/s at PA= 220° (Yurchyshyn et al., 2005). Fast CMEs often propagate through the solar wind at Super-Alfvénic speeds, driving shocks ahead of them (Reiner et al., 2007). The shocks driven by halo CMEs are frequently responsible for driving large GSs (Gopalswamy et al., 2007a).

(iii) Table 3.5 shows correlations between CMEs features (Linear speed, acceleration) with Dst index and TT of CMEs. A correlation coefficient value -0.59 between CME linear speed and TT indicates a strong dependence of CME linear speed with its TT. The events of 29 October, 2003 (11:30 UT) and 18 November, 2003 (08:50 UT) strongly support these results having high linear speed 2029 km/s and 1660 km/s with low TT, 19:25 hrs and 23:53 hrs respectively are responsible for creating super-intense GSs. These two energetic events are examples of Halloween events. The October-November period of 2003 saw some of the most energetic solar flares and CMEs of solar cycle 23. These eruptive events came to be known as the Halloween Events (Manchester et al., 2008). We have found significant correlation coefficient between CME linear speed and Dst for southern event about -0.55 (Table 3.4). Thus, linear speed found to be more useful parameter for predicting the occurrence of major GSs for the southern halo CMEs than northern halo CMEs. About 73.5% of fast halo CMEs (having speed higher than 1000 km/s) and about 61% halo CMEs (having speed between 500 km/s and 1000 km/s) are the cause of major GSs (Prasad, Garia & Bhatt, 2013).

(iv) Table 3.6 shows flare class associations with GS. The percentages of numbers of intense and super-intense GSs associated with CME of different flare classes. About
53% of total halo CMEs associated with X-class flares are responsible for super-intense storm and 36% for intense storm, which are highest in number in comparison of halo CMEs belonging to other classes of flares. Thus, it is clear from this table that halo CMEs associated with X-Class flares are more geo-effective according to halo CMEs data from 2000-2005. It is clear from Table 3.3 that out of 14 super-intense GSs 8 belongs to X-class, 4 belong to M-class flare and 2 belong to C-class flare.

(v) The location of a halo CME plays an important role in creating GS. The halo CMEs occur from ±25 of Heliospheric latitude (1 exception) and ± 30 of Heliospheric longitude (10 exceptions) are more geo-effective than other halo CMEs. In our investigation we find that 31 geo-effective CMEs in northern hemisphere against 22 geo-effective CMEs in southern hemisphere during 2000-2005.

3.5.1.4 Conclusions
We conclude the following from our study of 67 Halo CMEs from 2000-2005:-

(i) The TTs of CMEs show a great dependence on their linear speed. The fast halo CMEs with low TT are more geo-effective.

(ii) The halo CMEs associated with X-class flares are stronger candidates of GSs than halo CMEs associated with other classes of flares. Which is in agreement with the finding of Wang et al. (2002) but disagree with the finding of Zhang et al. (2003). Zhang study out 27 major GSs occurring between 1996 to 2000 and investigated that only 30% (eight events) are associated with major flares (M and X-class soft X-ray flares) but we find out about 53% of total halo CMEs associated with X-class flares are responsible for super-intense storm and 36% for intense storm.

(iii) The investigation suggests that geo-effective CMEs occur at low and moderate latitudes and are mainly the disk events. Thus, the location of CME is important in predicting the geo-effectiveness. Our result is in agreement with earlier results of Webb et al. (2000), Cane et al. (2000) and Gopalswamy et al. (2000).

(iv) The linear speed of halo CMEs can be a strong parameter for predicting the strength of GS mainly, for the southern halo CMEs.

Our statistical investigation of solar sources of intense and super-intense GSs that occurred during 2000 to 2005 reveals that fast halo CMEs associated with X-class
flares occur in low and mid latitude of sun can possibly be used for predicting the intense geomagnetic activity. Linear speed can be used as a predicting parameter for the southern halo CMEs only. However, for predicting the magnitude and onset time of GS it is also important to understand interplanetary consequences of geo-effectiveness.

### 3.5.2 Chree analysis by superposed epoch method

Chree (1912, 1913) introduced a method to investigate the possible relationship between two sets of observations. This technique is used to test the relationship between two diverse phenomena or to search for the periodicity in time series of data. This method is a procedure for analyzing one set of measurements during epoch selected on the basis of a specific type feature in the second set of measurements. In this method on the basis of some observational criterion (e.g., the day of occurrence of GSs or CME onset) N key days are associated with some variation in data under investigation (solar wind speed, solar wind pressure, IMF B_z component, cosmic ray intensity). Each key day is designated as the centre of an epoch (day zero) the length of which is selected on the basis of physically plausible period (27 day solar rotational period).

The method is a “Row × Column” array in which the response index values filling any row are date pertaining to a single key event. Here row represent the epoch and column represents day before and after the individual key days. The number of rows is the sample size of each event. The column line up to the index values in fixed time relative to the key times. The column averages than give the time variation of the parameter under study which can be represented in the form of graph. We described this technique in following steps-

**Step 1:** We collected the day average data of Dst and solar wind speed and selected those events having Dst $\leq -50$ nT (denoted by bold letters in Table 3.7).

**Table 3.7** Daily average data of Dst and Solar wind speed for the year 1997.

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<th>A- days of year,</th>
<th>B- solar wind speed (km/s),</th>
<th>C- Dst (nT)</th>
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In above data there are 10 GSs (epochs N=10) with Dst -50 nT.

**Step 2:** Now we have selected the Dst and solar wind speed from the above data on a time scale of 13 days (days: 6 days before and 6 days after the occurrence of GSs) and calculated their column average.

**Table 3.7.1:** The Dst data with their column average (bold numbers) for the year 1997.

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**Table 3.7.2:** The solar wind speed data with their column average (bold numbers) for the year 1997.

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<td>406</td>
<td>372</td>
<td>380</td>
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<tr>
<td>344</td>
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<tr>
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<td>420</td>
<td>369</td>
<td>333</td>
<td>432</td>
<td>510</td>
<td>524</td>
<td>404</td>
<td>367</td>
<td>356</td>
<td>359</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>363.1</td>
<td>390</td>
<td>382.8</td>
<td>367.7</td>
<td>366.5</td>
<td>400.8</td>
<td>441.1</td>
<td>420.3</td>
<td>390.1</td>
<td>368.9</td>
<td>349.7</td>
<td>346.4</td>
<td>341.6</td>
<td></td>
</tr>
</tbody>
</table>
Step 3: Thus, the average values of Dst and solar wind speed ($V_{sw}$) are in Table 3.7.3.

Table 3.7.3: The average values of Dst and solar wind speed from -6 to +6 days with respect to the occurrence of GSs.

<table>
<thead>
<tr>
<th>Day</th>
<th>-6</th>
<th>-5</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>+1</th>
<th>+2</th>
<th>+3</th>
<th>+4</th>
<th>+5</th>
<th>+6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dst</td>
<td>-13.7</td>
<td>-14</td>
<td>-12.7</td>
<td>-11.6</td>
<td>-13.4</td>
<td>-23.5</td>
<td>-61</td>
<td>-31.1</td>
<td>-23.9</td>
<td>16.9</td>
<td>14.2</td>
<td>-12.5</td>
<td>-10.9</td>
</tr>
<tr>
<td>$V_{sw}$</td>
<td>363.1</td>
<td>390</td>
<td>382.8</td>
<td>367.7</td>
<td>366.5</td>
<td>400.8</td>
<td>441.1</td>
<td>420.3</td>
<td>390.1</td>
<td>368.9</td>
<td>349.7</td>
<td>346.4</td>
<td>341.6</td>
</tr>
</tbody>
</table>

Step 4: Fig. 3.14 shows Chree analysis result of Dst and solar wind speed of 10 events for the year 1997.

Figure 3.14: The result of Chree analysis from -6 to +6 days with respect to zero epochs days. The variation of mean value of Dst index and solar wind speed are plotted. Zero days corresponds to the starting day of occurrence of GSs.

Since solar wind speed curve is maximum when Dst has the peak value. Thus, Our Chree analysis result is that enhanced solar wind speed near the earth is responsible for GSs and both peaked at same time for same duration.
3.5.2.1 Association between GS with Solar Wind and IMF features during 1997-2008

CMEs are the source of major disturbances in the interplanetary medium, which further produce sudden changes in the earth’s magnetosphere and cause GSs. The change in dynamic pressure of the solar wind and the orientation of the IMF is responsible to change the dynamic structure of earth’s magnetosphere. The IMF $B_Z$ generated (i) when high-speed plasma flow modifies the ambient IMF (Gosling & McComasa, 1987), (2) as a result of solar wind turbulence and wave generation (Velli & Pruneti, 1997), (iii) when magnetic field lines extended from the sun merges (Schindler & Birn, 1999), and (iv) due to the transportation of IMF $B_Z$ from the solar corona. Generally, when CME propagates, it enhances the speed of solar wind. Mostly, the common disturbances in IMF the directional changes associated with rotational discontinuity. The southern $B_z$ component of IMF is the most geo-effective parameter (Tsurutani et al., 1988).

We investigate the relationship among GSs and interplanetary parameters (plasma flow pressure, solar wind speed and IMF $B_Z$) for the time interval 1997-2009. We have taken IMF $B_Z$ component in Geocentric Solar Ecliptic (GSE) coordinate system. The present study investigates by means of superposed epoch analysis the Dst index of GS, IMF $B_Z$ component, solar wind speed and plasma flow pressure on a time scale of 13 days (days: 6 days before and 6 days after the occurrence of GSs).

3.5.2.2 Collection and analysis of data

We used Chree analysis by the super epoch method. The daily mean value of Dst, plasma flow speed, solar wind pressure and $B_Z$ component is taken from website http://omniweb.gsfc.nasa.gov/cgi/nx1.cgi and results are shown in Fig. 3.15 and Fig. 3.16. We further concentrate on southward $B_Z$ component of IMF and study the relation between strength of GS (moderate storm and intense storm) and north- south component of IMF during 1998 to 2005 (Fig. 3.17).
Figure 3.15: The result of chree analysis from -6 to +6 days with respect to zero epochs days. The variation of mean value of Dst index, IMF B\textsubscript{Z} and plasma flow pressure are plotted. Zero days corresponds to the starting day of occurrence of GSs during 1997-2006.
Figure 3.16 The result of Chree analysis from -6 to +6 days with respect to zero epoch days. The variation of mean value of Dst index and solar wind speed is plotted. Zero days corresponds to the starting day of occurrence of GSs.
Figure 3.17: It represents the result of Chree analysis from -6 to +6 days with respect to zero epoch days. The variation of mean value of Dst index and IMF B$_Z$ component is plotted. Zero days corresponds to the starting day of occurrence of GSs.
Table 3.8: The correlation coefficient among interplanetary parameters (IMF $B_z$, plasma flow pressure and solar wind speed) and Dst index.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameters</th>
<th>Correlation Coefficient (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dst index and $B_z$</td>
<td>0.62</td>
</tr>
<tr>
<td>2</td>
<td>Plasma flow pressure and solar wind speed</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>Dst and plasma flow pressure</td>
<td>-0.466</td>
</tr>
<tr>
<td>4</td>
<td>Dst index and solar wind speed</td>
<td>-0.45</td>
</tr>
<tr>
<td>5</td>
<td>$B_z$ and plasma flow pressure</td>
<td>-0.47</td>
</tr>
</tbody>
</table>

Table 3.9: The yearly variation in average southward magnitude of IMF $B_z$ component for moderate and intense GSs.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Year</th>
<th>$B_z$ for Moderate GSs</th>
<th>$B_z$ for Intense GSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1998</td>
<td>-3.1</td>
<td>-4.6</td>
</tr>
<tr>
<td>2</td>
<td>1999</td>
<td>-2.2</td>
<td>-5.2</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>-1.17</td>
<td>-4.9</td>
</tr>
<tr>
<td>4</td>
<td>2001</td>
<td>-1.45</td>
<td>-2.91</td>
</tr>
<tr>
<td>5</td>
<td>2002</td>
<td>-0.84</td>
<td>-3.81</td>
</tr>
<tr>
<td>6</td>
<td>2003</td>
<td>-2.58</td>
<td>-4.96</td>
</tr>
<tr>
<td>7</td>
<td>2004</td>
<td>-3.03</td>
<td>-6.9</td>
</tr>
<tr>
<td>8</td>
<td>2005</td>
<td>-1.5</td>
<td>-3.7</td>
</tr>
</tbody>
</table>

3.5.2.3 Results and discussion

In 11 years data, we found that the maximum numbers of GSs occurs in years 2002, 2001 are 35 and 37. The minimum (zero) GSs occurs in 2008, 2007. This is due to the fact that 2002, 2001 are the year of maximum solar activity whereas 2008, 2007 are the years belong to the minimum phase of solar cycle 23.
On analysis of data, we found that the plasma flow pressure is maximum one day before the GSs whereas solar wind speed is maximum during the GSs (Fig 3.15 & 3.16). It implies that the ring current injection increases when the magnetosphere is more compressed by high plasma flow pressure (solar wind dynamic pressure) near the earth. When CME from the sun propagates in interplanetary space it creates disturbances in solar wind. ICME (CME in interplanetary space), when arrive near the earth it contains compressed solar wind plasma ahead of high speed solar wind. This compressed solar wind plasma exerts a dynamic pressure on earth’s magnetosphere. When we calculated the correlation coefficient between plasma flow pressure and solar wind speed, it was found that there is a high positive correlation ($R=0.89$), which implies that both interplanetary parameters are highly related to one another and enhanced value of these parameter is responsible for GSs. There is a linear positive correlation between IMF $B_Z$ and Dst with a correlation coefficient 0.62. The all GSs occurred when IMF $B_Z$ is southward (e.g., $B_Z$ is negative) near the earth during 1997 to 2008.

When we analyses the Fig. 3.17 we found that $B_Z$ component is negative during GSs. However the peak values of GSs and southward component of IMF do not occurs simultaneously. We also notice that the strength of GSs does not depends on the magnitude of $B_Z$ component even a large southward value of IMF $B_Z$ component can produce a moderate GS. It is because the southward $B_Z$ is important to trigger the GSs but the strength of GSs may depends on the combined effect of some other interplanetary conditions near the earth at that time.

We also find that the time lag between maximum southward $B_Z$ component and GSs peak value is about a day. When we comprises the maximum southward IMF component with solar activity cycle we find an interesting result that its value (southward $B_Z$) is decreasing as the solar activity cycle approaches to its maximum activity phase and then raising and suddenly again a decrease in year 2005 (Table 3.9).
3.5.2.4 Conclusions

The disturbances in IMF are solar related directly as CME initiated shocks or indirectly through solar wind stream interaction. Thus, we found that

(i) The plasma flow pressure enhancement is followed by enhanced solar wind speed near the earth and this enhanced solar wind speed (>440 km/s) mostly occurs during GSs.

(ii) Plasma flow pressure together with solar wind speed near the earth is a geoeffective parameter, when IMF $B_Z$ is southward.

(iii) The strength of GSs directly depends on the magnitude of plasma flow pressure near the earth.

(iv) The GSs and $B_Z$ component is highly correlated but the peak value of southward $B_Z$ and peak value of Dst not occur simultaneously.

(v) The Southward IMF $B_Z$ component is responsible to trigger GSs.

(vi) The strength of GSs do not depends on the southward magnitude of IMF $B_Z$ component.

(vii) The maximum time lag between the peak value of southward IMF $B_Z$ component and GSs is about a day.

(viii) The average behavior of maximum magnitude of southward IMF $B_Z$ component represents just opposite nature with respect to solar activity cycle.

Therefore, plasma flow pressure, solar wind speed and IMF $B_Z$ are together are effective parameters to trigger GSs.