CHAPTER 4
ASSOCIATION BETWEEN CME, GS AND FD IN COSMIC RAY
Chapter 4
ASSOCIATION BETWEEN CME, GS AND FD IN COSMIC RAY

4.1 Introduction

CMEs and the shocks they drive cause cosmic ray FDs on the ground. The same phenomena are also responsible for GSs. FDs in cosmic ray and GSs belong to components of the space weather, which affect the earth’s atmosphere. Thus, FDs provide valuable, complementary information about space weather disturbances. Furthermore, certain phenomena associated with FDs, such as precursory decreases and spatial anisotropies can provide advance information regarding the intensity of GSs.

4.2 Cosmic Rays

Cosmic rays of extraterrestrial origin were first recorded by Victor F. Hess, 1912) with help of electrometers carried to high altitudes in balloons and for which he won the Nobel Prize in 1936. In the 1920s the term "Cosmic Rays" was coined by Robert Millikan by measurements of ionization due to cosmic rays from deep under water to high altitudes and around the globe. Cosmic rays are broadly defined as massive, most energetic (energy up to $10^{21}$ eV) particles that arrive at the earth from anywhere beyond its atmosphere. They provide information about the composition of astrophysical sources in our immediate neighborhood and out of our galaxy. The showers of secondary particles produced by primary cosmic rays penetrate and impact the earth's atmosphere and sometimes even reach the surface. The cosmic ray primarily composed of high-energy protons and atomic nuclei. Cosmic rays include:


Part of this work has been submitted (L. Prasad, B. Bhatt & S. Garia ) in “Astronomysche Nachrichten” US, 2014.
4.2.1 Galactic Cosmic Rays (GCRs)

The GCRs come from outside of the solar system, propagate from the heliopause to the inner heliosphere, where they experience the Lorentz force and are scattered by irregularities such as the Alfvén and MHD turbulence in the interplanetary medium. GCRs are mostly atomic nuclei and electrons, because the atoms stripped off the electrons during their passage through the galaxy at relativistic speeds. Cosmic rays of galactic origin are incident continually and isotropically on our solar system. The isotropic nature of GCR is because of the intervening turbulent magnetic fields, which "scramble" the directions of the charged particles presented in cosmic ray. GCRs have difficulty in reaching inner solar systems because they are blocked and scattered by transient inhomogeneities in interstellar space and IMF embedded in the solar wind. Some GCRs which successfully enter in inner solar system are modulated by solar activity. It is known that with increase of solar activity the fluctuations of the irregularities and transient inhomogeneities in the heliosphere increases, which block and scatter the GCR. Thus, only few GCRs are able to penetrate the inner heliosphere and the earth.

4.2.2 Anomalous Cosmic Rays (ACRs)

ACRs are those particles in energy spectra of cosmic rays that originate as interstellar neutral gas atoms flowing into heliosphere. They are unexpectedly low energy cosmic rays coming from interstellar space at the edge of the heliopause (edge of our solar system), in the heliosheath. The electrically neutral atoms are able to enter the heliosheath (being unaffected by its magnetic fields) get ionized and are thought to be accelerated into low-energy cosmic rays by the solar wind's termination shock which marks the inner edge of the heliosheath. There is a possibility that high energy GCRs which hit the shock front of the solar wind near the heliopause and decelerated, which results lower-energy ACRs. They include large quantities of helium, nitrogen,
oxygen, neon, argon and other elements with their high ionization potential. Therefore, the ACR consist of those elements which are difficult to ionize. The “anomalous” name is given due to their unusual composition. Some of the penetrating neutral atoms of ACRs near to the sun get ionized either by photoionization or by charge exchange. Sun’s magnetic field picks up these charged particles and carries them outward to the solar wind termination shock where they are eventually accelerated (Pesses, Jokipli & Eichler, 1981). ACRs are less than fully ionized and they are not affectivity deflected by earth’s magnetic field as GCRs in same energies.

4.2.3 Solar Cosmic Rays (SCRs)

Sun release its energy constantly in three modes- the first is black body radiation mode (sunlight), the second mode is solar electromagnetic emission (X-ray and UV radiation) mostly absorbed above the earth’s stratosphere. The third mode of solar energy emission is in the form of particles where the lower energy particles are referred as solar wind and higher energy particles are SCRs or SEPs. SCRs are cosmic rays with relatively low energy (10-100 keV). The average composition of SCR is similar to that of the sun itself.

The SCRs vary widely in their intensity and spectrum. The strength of SCRs increases after some solar events such as CMEs and solar flares. Ground level enhancements (GLEs) of SCRs are the solar particle events that can be recorded from ground based detectors as sharp increases of short duration in the cosmic ray intensity counting rates. These energetic particles recorded by the neutron monitors must have energies of at least 500 MeV in order to access the earth’s magnetosphere and to be recorded at the ground as secondary cosmic rays (Simpson, 2000). Also, an increase in the intensity of SCRs is followed by a decrease in all other cosmic ray intensity (FD) because the solar wind with its entrained magnetic field sweeping some of the GCRs outwards, away from the sun and earth. The overall or average rate of FDs tends to follow the 11 year sunspot cycle, but individual events are tied to events on the sun.

Generally, the particles of SCRs have lower energies than those of GCRs (their energy spectrum is softer). The energies of protons usually are limited to fractions of a GeV and the lower boundary of the energy of the recorded electrons of SCRs is of
the order of tens of keV (close to the energy of the particles of the solar wind). However, during some chromospheric flares the fluxes of SCRs are hundreds times more powerful than the fluxes of GCRs (the protons with energies up to 100 GeV are generated). This may cause a serious threat to the safety of space flights. Therefore, systematic observations of CMEs, flares, outbursts at radio-frequency and X-radiation, and other manifestations of solar activity, make possible the prediction of radiation conditions on the routes of space flights are very important.

On the average, there is high contribution of SCRs to the total intensity of cosmic radiation. The chemical composition of SCRs is very close to the composition of the solar atmosphere and not contain Li, Be, or B nuclei. This shows that the quantity of matter penetrated by SCRs is extremely small (< 0.1 g/cm²) and that they cannot be generated in the depths of the solar atmosphere, where the density of matter is too great. The acceleration of SCRs particles takes place mostly in the outer chromosphere and inner corona of the sun.

4.2.4 Ultra High Energy Cosmic Rays (UHECRs)

The particles of UHECRs have energy exceeding $10^{20}$ eV. This is enough energy to accelerate the single proton to 99.99% of speed of light. They hit the earth at the rate of ~ 1/km² per century (Fig. 4.1). The supernova, gamma ray burst or anything else at cosmological distances cannot generate UHECRs (Semeniuk, 2003). It is considered that their origin is extragalactic perhaps the core of active galactic nuclei in powerful radio galaxies or by cosmic strings.

4.3 Primary Cosmic Rays

Cosmic rays produced in various astrophysical processes outside of earth's atmosphere, originate as primary cosmic rays. The primary cosmic rays consist of about 99% nuclei (stripped of their electron shells) of well-known atoms, and about 1% solitary electrons (similar to beta particles). Of the atomic nuclei, about 90% are simple protons (hydrogen nuclei), approximately 7% are alpha particles, the nuclei of elements heavier than hydrogen and helium account for only a small fraction (~ 1
percent) and a very small fraction are stable particles of antimatter, such as positrons or antiprotons. Despite this, nuclei with $Z > 1$ carry about 50 percent of the energy in cosmic rays. The decrease in the abundance of an element increases more slowly in cosmic rays with an increase in atomic number than for the matter in heavenly bodies consist in the universe. The content of the nuclei of the light elements lithium (Li), beryllium (Be) and boron (B) is especially great in cosmic rays [Generally, The natural abundance of Li, Be and B is extremely small ($\leq 10^{-7}$ percent)]. There is also an excess of heavy nuclei ($Z \geq 6$). Thus, the acceleration of heavy nuclei predominates in the sources of cosmic rays and lighter nuclei arise as a result of the disintegration of heavy nuclei (fragmentation) after interaction with interstellar matter. In the period

**Figure 4.1:** The differential energy spectrum of GCRs. The arrows and the value given in brackets indicate the integrated flux above the corresponding energies (Swordy, 2001).
1966–71 nuclei heavier than iron were detected in cosmic rays by using nuclear photographic emulsions and solid-state charged-particle detectors. In the most thoroughly studied energy region (> 2.5 GeV per nucleon), the nuclear composition of cosmic rays is as follows: protons about 90 percent; alpha particles about 7 percent; nuclei with $Z = 3–5$ about 0.1–0.15 percent; $Z = 6–9$ about 0.5 percent; $Z = 10–15$ about 0.1–0.15 percent; $Z = 16–25$ about 0.04 percent; $Z = 26$ (iron) about 0.025 percent; and $Z > 30$ approximately $\sim 10^{-5}$ percent. The precise nature of remaining fraction is an area of active research.

**4.4 Secondary Cosmic Rays**

When cosmic rays enter the earth's atmosphere they interact with molecules, mainly oxygen and nitrogen and produce a cascade of lighter particles, a so-called air shower (Morison, 2008). Thus, secondary cosmic rays, caused by a decay of primary cosmic rays when they impact an atmosphere, include neutrons, pions, positrons, and muons produced in collisions. All of the produced particles stay within about one degree of the primary particle's path.

Muons are the typical particle, which are able to reach the surface of the earth, and even penetrate for some distance into shallow mines. These muons can be easily detected by many types of particle detectors (cloud chambers, bubble chambers or scintillation detectors). Cosmic rays impacting other planetary bodies in the solar system are detected indirectly by observing high energy gamma ray emissions by gamma-ray telescope. These are distinguished from radioactive decay processes by their higher energies above about 10 MeV.

**4.5 Cosmic Ray Sources**

Generally, the rotating neutron stars, supernova, radio galaxies, quasars and black holes are the extra solar source of cosmic rays. However, the some extremely high energies cosmic rays provide evidence of extra-galactic origin of cosmic ray because the local galactic magnetic field would not be able to contain particles with such a high energy. The origin of cosmic rays with energies up to $10^{14}$ eV can be accounted for in terms of shock-wave acceleration in supernova shells. During each supernova
explosion expansion of the shell of the star takes place at tremendous velocity and shock waves that cause acceleration of charged particles to energies of \( \sim 10^{15} \) eV and higher arise in the plasma (Fig. 4.3). This intensive acceleration of heavy charged particles (protons and nuclei) also takes place in the expanding shells of supernovas, in addition to the acceleration of electrons. This acceleration causes the “leakage” of such nuclei out of the dense stellar shell which contains high magnetic field. It is assumed that approximately 1 percent of the total energy release of each explosion \( (10^{51} - 10^{52} \text{ erg}, \text{ or } 10^{63} - 10^{64} \text{ eV}) \) is lost to accelerate heavy charged particles. This explains both the average energy density of cosmic rays \( (\sim 1 \text{ eV/cm}^3) \) and the absence of appreciable fluctuations in the cosmic-ray flux. Heavy charged particles that have been accelerated in galactic sources then propagate along complex trajectories in interstellar space.
The weak, irregular and non-uniform magnetic fields of the interstellar plasma clouds act on charged particles and they are “lost” in these magnetic fields, whose intensity increases significantly in the regions of the spiral arms of the galaxy. Here the motion of cosmic rays has the character of diffusion, resulting in almost complete isotropy of the flux of cosmic particles.

Methods of radio astronomy have been used to record more powerful sources of cosmic rays that are located far beyond the boundaries of our galaxy. These sources are quasars, the nuclei of some galaxies that experience abrupt explosive-type expansion and radio galaxies.

Solar energetic particles (SEP) originate during onset of CMEs and solar flares events. Since they originate along magnetic field lines connected to coronal flare sites, their acceleration could be governed by the same magnetic reconnection process that governs the associated flare. SCR particles are accelerated by coronal and interplanetary effects of solar flares and/or CMEs.

Fundamentally the new possibilities for the experimental study of sources of the most energetic cosmic-ray (up to energies of $10^{20}$–$10^{21}$ eV) opened up after the detection of cosmic ray particles.
pulsars. The pulsars are small neutron stars (about 10 km in diameter) formed as a result of the rapid gravitational compression of unstable supernova-type stars. Further, this gravitational collapse increases the density of a star’s matter magnetic field (up to $10^{13}$ gauss) and rate of rotation (up to $10^3$ revolutions per sec) tremendously. These create favorable conditions for the acceleration of heavy charged particles to ultra high energies (of the order of $10^{21}$ eV).

4.6 Detection of Cosmic Rays

The atomic nuclei that constitute cosmic rays interact strongly with other matter, collide with the nuclei of atmospheric gases during its travel toward earth and produce a shower. These collisions results the production of many Pions and Kaons, unstable Mesons which further decay into muons quickly. The muons do not interact strongly with the atmosphere and many of them are able to reach the surface of the earth. The ionizing radiation (muons) may easily be detected by many types of particle detectors such as bubble chambers or scintillation detectors. If muons are observed by separated detectors at the same instant then only a shower event will responsible for it. When cosmic ray reacts with interstellar gases, the result is a gamma ray that can be traced back. The results of spacecraft indicate that many of the gamma rays appear to come from the direction of supernova remnants. Modern electronic detectors called Charge Coupled Devices (CCDs) are effective cosmic ray detectors. When a cosmic ray strikes a single pixel, make it much brighter than the surrounding ones.

The ground-based methods of detecting cosmic rays currently in use is the air Cherenkov telescope, able to detect low-energy ($<$200 GeV) cosmic rays by analyzing their Cherenkov radiation, which for cosmic rays are gamma rays.

While these telescopes are extremely good at distinguishing between background radiation and that of cosmic-ray origin, they can only function well on clear nights without the moon shining, have very small fields of view and are only active for a few percent of the time. Another Cherenkov telescope uses water as a medium through which particles pass and produce Cherenkov radiation to make them detectable.
Extensive Air Shower (EAS) arrays, a second detection method, measure much higher-energy cosmic rays than air Cherenkov telescopes, can observe a broad area of the sky and can be active about 90% of the time. However, they are less able to segregate background effects from cosmic rays than can air Cherenkov telescopes. EAS arrays employ plastic scintillators in order to detect particles.

Another method was developed by Robert Fleischer, P. Buford Price and Robert M. Walker for use in high-altitude balloons (Fleischer et al., 1975). In this method, sheets of clear plastic, like 0.25 mm Lexan polycarbonate, are stacked together and exposed directly to cosmic rays in space or high altitude. The nuclear charge causes chemical bond breaking or ionization in the plastic. At the top of the plastic stack the ionization is less, due to the high cosmic ray speed. As the cosmic ray speed decreases due to deceleration in the stack, the ionization increases along the path. The resulting plastic sheets are "etched" or slowly dissolved in warm caustic sodium hydroxide solution that removes the surface material at a slow, known rate. The caustic sodium hydroxide dissolves at a faster rate along the path of the ionized plastic. The net result is a conical etch pit in the plastic. The etch pits are measured under a high-power microscope and the etch rate is plotted as a function of the depth in the stacked plastic. This technique yields a unique curve for each atomic nucleus from 1 to 92,
allowing identification of both the charge and energy of the cosmic ray that traverses the plastic stack. The more extensive is the ionization along the path, the higher the charge. In addition to its uses for cosmic-ray detection, this technique is also used to detect nuclei created as products of nuclear fission.

A fourth method involves the use of cloud chambers (to detect the secondary muons created when a pion decays. Cloud chambers in particular can be built from widely available materials and can be constructed even in a high-school laboratory. A fifth method, involving bubble chambers, can be used to detect cosmic ray particles (Chu et al., 1970).

4.7 Effects of Cosmic Rays and Their Role in Ambient Radiation

Cosmic rays constitute a fraction of the annual radiation exposure of human beings on earth. For example, the average radiation exposure in Australia is 0.3 mSv [1 milli Sievert (mSv) = 100 Rad.] due to cosmic rays, out of a total of 2.3 mSv. The energetic particles, which are often detected by ground-based cosmic ray detectors as Ground-Level Enhancements (GLEs), can result in damage to satellite electronics and solar panels. Even a single event can upsets in ground-based electronic chips and other such effects. The other category of space weather effects arise from GSs (discussed in Chapter 3, Section 3.4.3).

Also, an observation of cosmic ray GLEs accompanying flare and/or CME provide constraints on the acceleration mechanisms and magnetic reconnection processes operative in the flares and/or CMEs.

4.7.1 Cosmic Rays Significance to Space Travel

Understanding the effects of cosmic rays on the body will be vital for assessing the risks of space travel. High speed cosmic rays can damage DNA, increasing the risk of cancer, cataracts, neurological disorders and non-cancer mortality risks. Due to the potential negative effects of astronaut exposure to cosmic rays, solar activity may play a role in future space travel via the FD effect. CMEs can temporarily lower the local cosmic ray levels, and radiation from CMEs is easier to shield against than cosmic rays.
4.7.2 Cosmic Rays Role in Lightning

Cosmic rays trigger the electrical breakdown in lightning. It has been proposed that essentially all lightning is triggered through a relativistic process, "runaway breakdown", caused by secondary cosmic ray (Gurevich & Zybin, 2005). The subsequent development of the lightning discharge occurs through "conventional breakdown" mechanisms.

4.7.3 Cosmic Rays Role in Cloud Formation

It is experimentally determined that cosmic rays are able to produce ultra-small aerosol particles, orders of magnitude smaller than cloud condensation nuclei. But the steps from production of ultra-small aerosol to modulation of cloud formation and to be a contributor of global warming have not been established. On a global scale, where earth's atmosphere acts as the cloud chamber analogous with the Wilson cloud chamber and the cosmic rays catalyze the production of cloud condensation nuclei. But real atmosphere always have many Cloud Condensation Nuclei (CCN) whereas in a cloud chamber the air is carefully purified. Various proposals given for explaining the exact mechanism for cloud formation by cosmic rays including Ion Mediated Nucleation, and through an indirect effect on current flow density in the global electric circuit (see Tinsley, 2000; F. Yu, 1999). The identification of GCR climate signals in atmospheric parameters such as high latitude precipitation (Todd & Kniveton, 2001) and originally Svensmark's annual cloud cover variations prove that cloud formation is more correlated to GCR variation than direct solar variation.

4.8 Modulation of Cosmic Rays

The flow rate (flux) of cosmic rays incident on the earth’s upper atmosphere is modulated by the sun’s solar wind and the earth's magnetic field. The solar wind decelerates the incoming particles partially excluding some particles having energies below about 1 GeV. Since the amount of solar wind is changes occur during eleven-year solar activity cycle, the level of modulation varies in autocorrelation with solar activity. Also, the earth's magnetic field deflects some of the cosmic rays because the intensity of cosmic radiation is dependent on latitude, longitude and azimuth. The
cosmic flux also varies from eastern and western directions (the east-west effect) due to the polarity of the earth’s magnetic field and the positive charge dominance in primary cosmic rays. The cosmic ray intensity at the equator is lower than at the poles (geomagnetic cutoff value is greatest at the equator) because charged particle tend to move in the direction of field lines. The field lines curve down towards the earth’s surface at the pole, this is the reason that the aurorae occur at the poles. An interplanetary disturbance, propagating from the sun to the earth, affects the GCR population in many ways. One of the most known effects is the FD.

4.8.1 Modulation of GCRs by the Solar Wind

Among the various periodic variations with time in the intensity of GCRs, modulations of GCR intensity play the primary role. The modulations are related to the scattering and “sweeping” of GCR by solar wind. The solar wind entrained in IMF varies according to 11-year cycle of solar activity so the cosmic ray intensity also varies according the solar cycle. The intensity of cosmic ray declines during peak solar activity in comparison with the magnitude characteristic of minimum activity.

There are also other types of modulation of GCRs caused by the 27-day variations in the period of the sun’s rotation around its axis, the daily solar variations associated with the earth’s rotation and with the anisotropy of the electromagnetic properties of the medium in which GCR propagate. It was stated by many investigators that the effective dimensions of the region in which cosmic rays are modulated by the solar wind is 2–5 AU.

4.8.2. Geomagnetic Effects on Primary GCRs

The primary cosmic rays flux reaching the earth from our galaxy is isotropic to a high degree of accuracy and is independent of direction. The charged particles in cosmic radiation are deflected from their original direction when they enter the earth’s magnetic field due to the action of the Lorentz force. Therefore, the intensity and energy spectrum of cosmic rays in near space depend both on the geomagnetic coordinates of the observation site and on the direction of arrival of the cosmic rays (Fig. 4.5).
The greater the angle \( \theta \) between the direction of motion of a particle and the direction of the field line of force, the more strongly geomagnetic field deflected. Thus, for a given particle energy the deflecting action of the geomagnetic field is maximum in equatorial regions and minimum near the magnetic poles. Near the equator the “geomagnetic barrier” does not allow to pass protons having energy less than \( \sim 15 \) GeV and nuclei with an energy less than \( \sim 7.5 \) GeV per nucleon (a proton or neutron) that comes perpendicular to the surface of the earth. This threshold energy of the particles decreases rapidly as the geomagnetic latitude increases \( \sim \cos^4 \phi \) and in the polar regions the geomagnetic barrier is virtually absent. In addition to the regular latitude dependence, anomalies of the geomagnetic field (especially in the region of the South Atlantic) appreciably affect the intensity of cosmic rays. Thus, the distribution of the intensity of cosmic rays over the earth is very complex (see Fig. 4.5). In the polar regions \( (\theta \geq 60^\circ) \) the intensity of cosmic rays at the boundary of the atmosphere in years of minimum solar activity is about 0.4 particles/cm\(^2\)/sec per unit of solid angle.

The average quantity of matter through which cosmic rays pass enroute from their sources to the earth has been estimated at \( 3-5 \) g/cm\(^2\). This study is on the basis of the presence in cosmic rays of Li, Be and B, which are formed as a result of fragmentation. Hence, if the average density of matter in the galaxy is known, the distance traveled by cosmic rays in our galaxy and the average lifetime of cosmic rays may be estimated.

Within the earth’s magnetosphere, at altitudes of \( \geq 1,000 \) km, much more intense fluxes of protons and electrons form the earth’s radiation belt which are captured by the geomagnetic field are present in addition to the cosmic ray flux. The origin of the internal region of the radiation belt is mainly due to the neutrons decay into protons and electrons, which are confined in the natural magnetic trap of the earth’s magnetosphere.

Low energy SCR has a significant impact on the condition of the earth’s ionosphere. They induce additional ionization of its lower layers leads to the attenuation of radio
waves and total loss of shortwave radio communications. Data on the propagation, energy spectrum and angular anisotropy of SCRs provide information on the structure of the magnetic field in interplanetary space. The study of spatial and temporal variations in fluxes of SCRs is helpful in gaining a better understanding of such geophysical phenomena as GSs and the aurora polaris. The nature of the increase in the flux of SCRs to earth shows that in the initial period after a flare the flux is largely anisotropic, and its maximum is directed at an angle of approximately 45° to the west of the direction of the sun. This was the first direct proof of the curvature of the lines of force of the IMF in the form of Archimedes spirals.
4.9 FDs in Cosmic Ray

A Forbush Decrease (FD) is a transient and rapid depression in the GCR intensity (after the increase in solar activity) followed by gradual recovery typically lasting several days (Forbush, 1938). They are believed to be caused by a shielding effect of the magnetic fields and flow configuration that propagates away from the sun. It is known that FD is observed during the passage of shock associated interplanetary disturbances although not all such interplanetary structures are able to produce this decrease.

The interplanetary disturbances like ICMEs caused by solar activity lead to change the flux of cosmic ray, which generally occurs as a sharp decreases of flux of secondary cosmic rays at a ground level. Cane (1996) reported a significant relationship between CMEs and cosmic ray variations. Iucci (1984) reported the idea of spiral cone like region which extend along the IMF. They have also the separate configuration of shock front and the following magnetic perturbations to the amplitude of the first and second step of FD as a function of associated solar flare longitudes. Interplanetary shocks near 1AU have large scale sizes, radii of curvature of the order of 1AU or about $10^3$ times of earth bow shock. A wide range of shock orientations ranging from quasi-perpendicular to quasi-parallel are observed (Tsurutani & Lin, 1985). These classifications are based on $Q_{Bn}$ (the angle between shock normal and extreme magnetic field direction). A shock is quasi-parallel when $0^\circ < Q_{Bn} < 45^\circ$ and quasi-perpendicular when $45^\circ < Q_{Bn} < 90^\circ$ (Quest, 1988).

Generally, quasi-parallel shocks consist of broad magnetic profile and are turbulent. In contrast, a quasi-perpendicular shocks are laminar and less turbulent (Smith, 1983; Quest, 1985). The broad turbulence in quasi-parallel shocks appears as large magnetic field fluctuations (Papadopolus, 1985). Quest (1983) observed that ions transmitted through the quasi-parallel shocks are strongly heated due to strong magnetic turbulence behind the shock front and so consist of large amplitude magnetic turbulence. These turbulent quasi-parallel shocks are more effective in modulating cosmic rays than non turbulent quasi-perpendicular shocks (Badruddin, 2002). The Field enhancements associated with high speed streams from coronal holes are not very effective in producing FDs. If the shock responsible for the FD is not turbulent...
enough and has a rather ordered structure, then the shock drift mechanism (suggested by Chang, Sarris, & Dadopoulous, 1990) will be the process responsible for this decrease. On the other hand, if the shock responsible for FD is turbulent enough then the scattering by turbulent fields in the shock environment will be the process responsible for the decrease.

Some interplanetary disturbances like the interplanetary counterparts of CME can cause depressions in high energy cosmic rays along the IMF main direction, being detected before the arrival of the CME to the earth (Munakata et al., 2000), according to the diagram shown in Fig. 4.6.

![Figure 4.6: Loss cone precursors (Nagashima et al., 1992; Ruffolo, 1999).](image)

Cosmic ray particles traveling close to light speed from this “depressed” region are observed as a “loss-cone precursor” at earth typically 4 to 8 hours before the arrival of the interplanetary disturbance (Munakata et al., 2000). FDs are observed by ground detectors, when the IMF disturbances pass by the earth’s magnetosphere. Since ICME structures are the main cause of intense GSs, so cosmic ray loss-cone precursors well are used to forecast space weather variability.

FDs may be large and small, short and long lasting, with fast and gradual recovery, two step or not, and so on. These variations in cosmic ray are due to diversity of solar sources and verity of interplanetary situation arising before and during the event. There are two basic types of FD (Cane, 2000):
(a) **Non-recurrent decreases** which are caused by transient interplanetary events related to CMEs from the sun, are marked by a sudden onset, reach their maximum depression in about a day, and are characterized by a gradual recovery.

(b) **Recurrent decreases** have a gradual onset and are symmetric in profile; and tend to be associated with corotating high speed solar wind streams (Lockwood, 1971; Iucci et al., 1979a).

### 4.9.1 ICMEs and FDs

The sun releases an exceptionally large burst of matter and magnetic disturbance, which sweep away some of the cosmic ray particles in its path and also prevents many cosmic ray particles to entering the earth’s atmosphere. Cane (2000) stated that the two step FDs are caused by the combination of shock and CMEs, the first step is connected to the turbulent structure behind the shocks, and second step is connected to the enhanced magnetic field and loop like field configuration of the CMEs.

It is well known that charged particles cannot freely move “across” magnetic field lines. A typical charged particle is caught by a magnetic field line in a circular trajectory and radius (called the gyroradius or Larmor radius) is directly proportional to the speed of the particle and inversely proportional to the strength of the magnetic field. The CME-driven shock compresses plasma ahead of it. If it is assumed that the magnetic field is frozen into the plasma, it follows that the magnetic field strength is enhanced in the vicinity of the shock. As the shock passes the earth, it acts as a shield of sorts against the ambient population of cosmic rays, since they cannot easily diffuse across the enhanced magnetic field in the vicinity of the shock. This leads to a decrease in the intensity of cosmic rays when the earth is within the shock; this is manifested as part of the observed FD. In reality, the magnetic field has an ordered, as well as a turbulent component. Cosmic rays generally diffuse through the tangled, turbulent magnetic field and this diffusion process is inhibited in the vicinity of the shock, which has a strong ordered magnetic field component. It is the inability of the cosmic ray particles to diffuse efficiently across the shock front that causes the observed FD. Theoretical treatments of FDs model is the effect arising due to a general propagating region of enhanced turbulence/scattering and decreased diffusion (e.g., le Roux & Potgieter, 1991) or implicitly assume that the decrease is
only due to the shock (e.g., Chih & Lee, 1986). However, the ICME (that drives the shock) is also responsible for a substantial part of the FD and can be explained as follows: the CME can be thought of as a closed, low density magnetic “bottle” that expands as it propagates through interplanetary space.

The plasma inside the CME is largely devoid of high energy cosmic rays. As the CME propagates, the ambient cosmic rays try to diffuse into the CME. This diffusion process is inhibited due to the relatively organized, large-scale magnetic field that encloses it. Consequently, the interior of the CME has a lower density of cosmic rays in comparison to its surroundings. When ICME passes through the earth, this decreased density contributes to the observed FD.

Essentially, one would expect a two-step FD when the geometry is such that the earth encounters both the shock and the CME (i.e., its near-earth counterpart in form of a magnetic cloud). If only the shock makes its passage through the earth, the FDs can be expected to have only one step. However, such classical two step decreases are rare; they are also typically observed only with neutron monitors. Muon detectors, which detect much higher energy cosmic rays, are unlikely to exhibit two-step decreases.

4.9.2 FDs and GSs

Both FDs and GSs are created by the same disturbances of the solar wind but in different ways. The IMF $B_z$ component plays a key role to trigger the GS together with enhanced solar wind speed and dynamic flow pressure of plasma near the earth (Prasad, Garia & Bhatt, 2013). But IMF $B_z$ generally does not affect the FDs. The geomagnetic disturbances are determined by the local characteristics of solar wind flowing around the earth’s magnetosphere, whereas FDs is a result of the influence of whole large scale interplanetary disturbances.

Here, we investigate the relationship among CMEs, FDs and GSs for the time interval 1999-2005. The present study investigates by means of superposed epoch analysis the intensity of cosmic rays on a large time scale (days: 13 days before and 13 days after the CME onset).
Figure 4.7: The result of Chree analysis from -13 to +13 days with respect to zero epoch days. The variation of mean Dst value and mean value of percent deviation in cosmic ray intensity. Zero days corresponds to the starting day of occurrence of the CME event during 2000-2005.
4.9.2.1 Data Collection and Analysis

We used Chree analysis by the super epoch method. The daily mean value of cosmic ray intensity is taken from Moscow and Beijing have been used for the period 1999-2005.

The CMEs from 1999 to 2005 causing GSs (Dst -50 nT) have been identified from Cane and Richardson ICME list 2003, revised in 2008. The values of Dst index and cosmic ray intensity are taken from the websites http://wdc.kugi.kyotou.ac.jp/dst_final/195712/index.html and http://www.ngdc.noaa.gov/stp/solar/cosmic.html respectively. Here zero days corresponds to onset day of CME. We excluded those events whose onset time are not given in the list.

4.9.2.2 Results and Discussion

We have plotted daily mean values of cosmic ray intensity and the Dst index as illustrated in Fig. 4.7. It is clear from the figure that the maximum decrease in Dst (GS) takes place within 5 day after the occurrence of an event. Also, the average behavior of Dst shows more variation in 1999, 2000, 2001 and 2005. Since in solar cycle 23 the smoothed maximum are 1999, 2000 and 2001 so due to high solar activity the Dst shows more variation. But in case of cosmic rays, the percent deviation in cosmic ray intensity shows more variation in 2002 and 2005. Where, 2005 is the high solar activity year. Thus, the average behavior of Dst somewhat affected by solar cycle but FDs behavior doesn’t follow the solar activity cycle. We found that in GSs the key role is played by the sign of the Bz component of IMF (Prasad, Garia & Bhatt). But Bz component generally does not affect FDs magnitude.

In Fig. 4.8 halo CME are responsible for more intense GSs in comparison with non halo CMEs. We have selected 78 CME events during 1999 to 2005. Out of 78 CMEs 52 are halo CMEs and 26 are non halo CMEs. We observed that halo CMEs are more effective in causing GSs rather than non-halo CMEs. But in case of FDs, halo CME seems to be not so important because not all halo CMEs give rise to interplanetary shocks and sheath behind the shocks that may be effective in cosmic ray modulation.
Figure 4.8: The average picture of cosmic ray intensity and Dst under the influence of halo CMEs and non halo CMEs depicted by different symbols.

Figure 4.9: The average picture of cosmic ray intensity and Dst under the influence of high speed ICMEs and low speed ICMEs depicted by different symbols.

In Fig. 4.9 we found that ICMEs having high speed (speed 500km/s) are geo-effective more than low speed ICMEs (speed 500km/s) because the sheath of solar wind plasma upstream is compressed by fast ICMEs moving behind it and contains
large fluctuations. It further may produce large negative value of $B_z$ component of magnetic field and combines with increased density in the compressed sheath to make this region highly geo-effective. In case of cosmic rays, low speed ICMEs are the cause to create more variation in cosmic rays in comparison with high speed ICMEs because of more possibility of low speed ICMEs to interact with other ICMEs coming behind and form multiple ejecta. Vesques et al. (2001) showed that ICMEs contains multiple ejecta having topological boundaries between different plasma regions and a tangential discontinuity within the boundaries where energetic particle diffusion coefficients are much lower. This discontinuity dramatically reduces particle diffusion within ICME sheath region and makes it effective in causing FDs in cosmic rays.

### 4.9.2.3 Conclusions

Thus we found that

(i) GSs occur within 5 days after the onset of CMEs and variation in geomagnetic disturbances generally follows the phase of the solar cycle.

(ii) Halo CMEs are geo-effective more than non-halo CMEs.

(iii) Fast ICMEs are more geo-effective than slower ICMEs whereas slower ICMEs are more cosmic ray effective than fast ICMEs.
Estelar