International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-2, Issue-3, March 2015

Study of Large Geomagnetic Storms (GMSs) and Space Weather Impacts

Dr. Rahul Shrivastava and Dr. Subhas Chand Dubey

***Abstract*— Aim of this statistical is to define the various characteristics of large geomagnetic storms (GMSs) associated with D_{st} decreases of more than 100 nT, observed during solar cycle 23. Out of the selected 90 large GMSs, 51 are sudden commencement type and rest 39 is gradual commencement type Long-term and storm time variation as well as seasonal and solar cycle dependence of above mentioned GMSs have been analysed. The study of solar cycle 23 is remarkable for occurrence of large GMSs during its declining phase. Various types of geomagnetic disturbances and their possible solar and interplanetary causes are explained in this work that provides a better aspect to understand the space-weather phenomenon. Several solar-terrestrial inter-connection mechanism and new results have been discussed in the present study. The severe GMSs have also been discussed that are very harmful to us, and they affect our communication system, power system.**

***Index Terms*— GMSs, SSN, Space Weather, 11-year SC.**

I. Introduction

Solar output in terms of solar plasma and magnetic field ejected out into interplanetary medium consequently create the perturbation in the geomagnetic field. The 11-year solar cycle (SC) is the best known variability in the Sun. Geomagnetic activities have long been known to be correlated with solar activities [1]. Earlier studies show that large solar flares were responsible for interplanetary shocks and intense geomagnetic storms (GMSs). Many recent studies and Skylab observations show that active sunspot regions, coronal mass ejections (CMEs), eruptive prominences and disappearing filaments are the active energy emitting regions and they produce large interplanetary and geomagnetic disturbances. The correlations of CMEs and intense GMSs have been discussed for different periods by several authors [2-7].

There are two types of geomagnetic field variations termed as long-time variation and storm-time variations. The long-term variations are very useful to solar cyclical study of geomagnetic field variation as well as change in polarity of the Sun, climate change, plants growth rate and geological change of Earth's pole. The storm time variations deal the various characteristics of GMSs and their connection with solar source activities and interplanetary magnetic fields. All GMSs produce terrestrial effects to some degree. The great GMSs have a direct effect to us and create many adverse effects within ionosphere and Earth's magnetosphere.

Dr. Rahul Shrivastava, Physics Department, Govt. Girls College, Rewa (MP) 486 001, India.
Dr. Subhas Chand Dubey, Physics Department, S.G.S. Govt. P.G. College, Sidhi (MP) 486661, India.

II. Selection Criteria and Data Sources

The data of D_{st} indices obtained from the WDC-2 Kyoto D_{st} index service. The D_{st} index has been introduce by [8] and used for solar quiet daily variation. Data of the CME index were taken by LASCO onboard SOHO. The data of sunspot number (SSN), solar flare index (SFI), solar radio flux (SRF) and the solar energetic particle (SEP) events data were taken from the National Geophysical Data Center (NGDC).

III. Characteristics of Large GMSs

The Out of the selected 90 large GMSs, 51 was sudden commencement type and rest 39 is gradual commencement type. Long-term behaviour of yearly occurred sudden commencement, gradual commencement and total number large GMSs and their association with yearly mean sunspot number are plotted in Figure 1. Generally, large number of GMSs occurs during the maximum phase of solar cycle because many solar activities are vastly occurring during this time. Near minimum phase, a few of the GMSs are observed due to the presence of coronal holes and some other solar activities. Yearly occurrence of sudden commencement, total and gradual commencement storms have no significant correlation between the maximum and minimum phases for solar cycle 23. It is also find that occurrence of large GMSs during its declining phase is higher and shows controversial result measured at yet. SC- 23 is remarkable for occurrence of large GMSs during its declining phase.

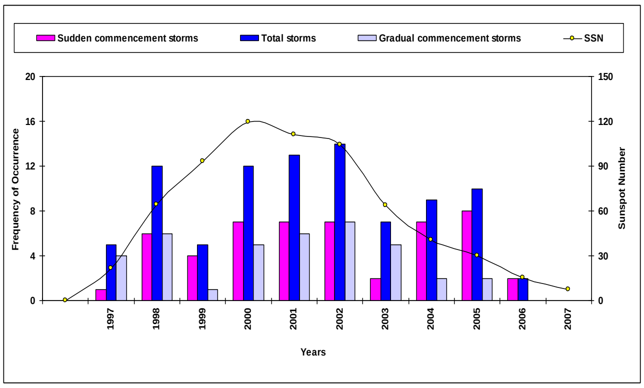

Fig 1. Association of yearly occurrence of sudden, gradual and total large GMSs with SC.

Long-term Variation of Sudden Storm Commencements

A shock wave is generated in the solar wind slams into the Earth's magnetosphere, produces a large magnetic impulse. This magnetic impulse is known as sudden storm commencement (SSC). It causes an instantaneous compression and distortion on the Earth's magnetosphere and increases geomagnetic activity lasting at least one hour. Once the initial shock wave has passed the solar wind returns to normal pressure and the magnetosphere recovers. Over the next several hours, the magnetic field remains fairly stable with only minor fluctuations. SSCs are caused by fast solar eruptions, but it is not necessary that all geomagnetic storms are beginning with a SSC.

We find 57% large GMSs were associated with SSCs. It is also observed that, in most of the cases, the onset of main phase just follows SSC. For the selected 90 large GMSs, the most probable value of time difference between SSC and onset of main phase is found to vary from 1-6 hours. We have also found that a number of SSCs have not been associated with any significant change in the D_{st} magnitude. It is also seen that the SSCs associated storms show faster recovery in comparison to the storms that are not associated with SSC.

The occurrences of solar activities vary with 11-year sunspot cycle, so it is important to investigate that how SSCs does show its variation. We have shown an association of yearly occurrence of SSCs for a long interval 1964-2007 that covers last 04 (20-23) solar cycle periods, and correlate it with yearly mean sunspot number. This association is plotted in Figure 2. It is found that the annually occurred value of SSCs follows with SSN during the period of solar cycle 22 and 23. During the period of solar cycle 20, these variations shows similar trends except some peculiarities, but solar cycle 21 is exceptional among these 04 cycles. During the period of solar cycle 21, annual mean sunspot numbers are as high as solar cycle 22, but number of occurred SSCs is less than other cycles. It is also observed that number of occurred SSCs is less during maximum of this cycle. These results indicate that it is not necessary that all fast solar eruptions caused the SSCs; it can differ from cycle to cycle.

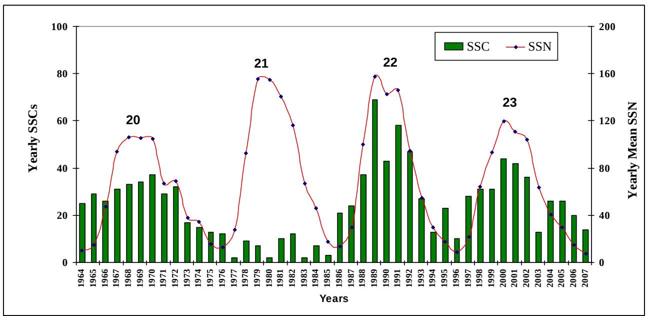

Fig 2. Association of SSCs with SC.

Long-term Variations of Solar Driver and Global A_p

A solar energetic particle (SEP) occurs when high-energy protons are ejected from the Sun's surface during fast solar eruptions and causes geomagnetic and ionospheric disturbances on large scale. These effects are similar to auroral events, the difference being that electrons and not protons are involved. These events typically occur at the north/south pole and South Atlantic magnetic anomaly, where the Earth's magnetic field is lowest. The more severe SEPs can cause widespread disruption to electrical grids and the propagation of electromagnetic signals. SEPs are an important cause to produce geomagnetic and ionospheric disturbances on large scale.

Solar flares (SFs) which are the most energetic explosions in the solar system have a direct effect on the Earth's atmosphere. The Earth's upper atmosphere becomes more ionized and expands. Long distance radio signals can be disrupted by the resulting change in the Earth's ionosphere. A satellite's orbit around the Earth can be disturbed by the enhanced drag on the satellite from the expanded atmosphere. Satellite's electronic components can be damaged. So a flare index is needed to study all the probable solar activities which affect our satellite environment and Earth atmosphere. Flare index (SFI) is one of the best indicators of activity variations on the chromosphere. This feature makes the flare index a suitable full-disk solar index for comparison with similar solar indices which reflect different physical conditions from the different layers of the solar atmosphere.

Kleczek [9] first introduced the quantity "$Q = i \times t$" to quantify the daily flare activity. In this relation, 'i and t' represents the intensity scale of importance and time duration (in minutes) of the SF. A SF is an enormous explosion in the solar atmosphere which is defined as a sudden, rapid and intense variation in brightness. It is believed to result from the sudden release of energy stored in the magnetic fields that thread the solar corona in active regions around sunspots involving sudden bursts of particle acceleration, plasma heating, and bulk mass motion. The SFI is a measure of this short-lived activity on the Sun. It represents total energy emitted by the SFs.

Geomagnetic disturbances are driven by the interaction of the solar wind with the Earth's magnetosphere, and the strength of this interaction depends on the solar wind parameters. Storm time changing phenomena are actively follows with solar wind velocity and strength of interplanetary magnetic field. The occurrences of solar source activities vary with 11-year sunspot cycle. We have established an association of global A_p, yearly occurrence of solar energetic particle (SEP) and flare index of solar activity (SFI) with annual mean sunspot number for a period 1997-2007. This association is depicted in Figure 3. We have found that the yearly occurred value of SFI varies with 11-year sunspot cycle except at some circumstances. It is also found that association of yearly occurrence of SEPs with 11-year sunspot cycle hasn't shows very significant correlation. The global geomagnetic activities are higher during solar maximum and *vice versa*. Figure 3 indicates that during the decline phase of solar cycle 23, global geomagnetic activities are higher and shows controversial results. These results also verified for late-cycle high-activity of SC- 23.

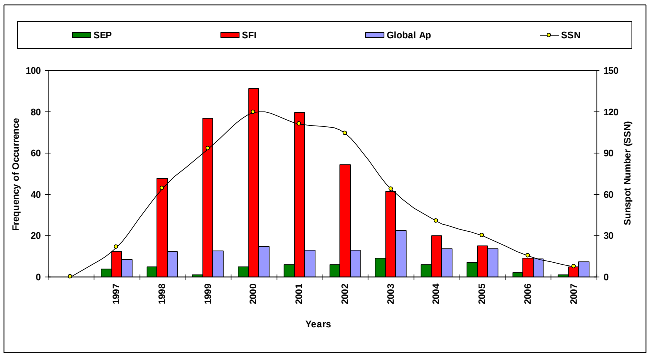

Fig 3. Association of global A_p, SEPs, with 11-year SC. Solar Maximum of Solar Cycle 23

Many recent studies indicate that CMEs and coronal holes (CHs) are mainly responsible for large GMSs. CMEs are often associated with SFs and prominence eruptions but they can also occur in the absence of either of these processes. The frequency of CMEs varies with the SC. We have analyzed 12 large GMSs occurred during the solar maximum period (2000) of solar cycle 23. Different responsible solar drivers of above mentioned storm events that are listed in Table 1. In the table, column (1) presents observed date of GMS. Column (2-4) represents magnitude of GMS in D_{st}, K_p and A_p respectively. Most probable solar drivers of concern large GMSs are noted in column (5).

Table 1: A list of 12 large GMSs observed during solar maximum year (2000) of solar cycle 23.

Date of GMS	D_{st}	K_p	A_p	Solar Driver
12/02/2K	-133	6.7	111	Single CME associated with SF (C 7.3)
07/04/2K	-288	8.7	300	Single CME associated with associated with SF(C 9.7) and SEP(55 MeV)
24/05/2K	-147	8	207	Multiple CME associated with SF (C 7.6 and C 6.3 respectively)
16/07/2K	-301	9	407	Single CME associated with SF (X5.7) SEP (24000MeV)
11/08/2K	-106	5.7	67	Single CME associated with SF (C 1.4)
12/08/2K	-235	7.7	179	Single CME associated with SF (C 2.3)
17/09/2K	-201	8.3	236	Multiple CME associated with SF (M 5.9, C7.4, M2.0 & C 9.5) and SEP (320 MeV)
05/10/2K	-182	7.7	179	Multiple CME (02 events) associated with SF (C 5.0)
14/10/2K	-107	5.7	67	Single CME associated with SF (C 6.7)
29/10/2K	-127	6	80	Single CME associated with SF (C4) and SEP (15 MeV)
06/11/2K	-159	7	132	Single CME
29/11/2K	-119	6.7	111	Multiple CME associated with SF (X 4.0 & X 1.9 respectively) and SEP (940 MeV)

It is observed that all 12 large GMSs occurred during solar maximum of solar cycle 23, are associated with CMEs. Out of 12 GMSs, 04 were caused by multiple CME and rests 08 were caused by single CME. Out of 12 CME associated GMSs, 11 were caused by CME associated with SFs and 05 were caused by CME associated with SFs and SEPs. GMSs associated with only single/multiple CME associated with SFs or not, having comparative low magnitude in comparison to that GMS which is caused by CME associated with intense SFs and SEPs of higher energies. A bigger SEP event of the solar cycle 23 occurred on 14th July 2000 having peak energy (pfu~24000 MeV).

Case Studies

GMS s are intervals of time when a sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial injection of energy into the magnetosphere-ionosphere system, to an intensified ring current, strong enough to exceed some key threshold of the quantifying storm time D_{st} index. During aforesaid period two severe GMSs ($D_{st} \leq$ -250 nT) were observed. These GMSs are observed at 7th April 2000 and 16th July 2000 respectively. These GMSs were related to CMEs observed by the Large Angle and Spectroscopic Coronagraph (LASCO). The sources of interplanetary southward magnetic field, B_s, responsible for the occurrence of the GMSs were related to the intensified shock/sheath field, interplanetary magnetic cloud's field, or the combination of sheath-cloud or sheath-ejecta field. We found that shock/sheath compressed fields are the most important interplanetary causes of severe GMSs during this period. We found that shock/sheath compressed fields are the most important interplanetary causes of severe GMSs.

7th April 2000 Severe Geomagnetic Storm

On 4th April 2000 (16:32 UT), a CME was observed to leave the Sun. Although the ejecta was not believed to be directly earthward, the sheath region between the shock front and the driver gas hit the Earth's magnetosphere, causing the largest GMS of 2000, as measured by the low-latitude D_{st} index. This fast CME was associated with SF (C 9.7/2F) with expansion speed of around 1927 km s^{-1}, spreading all around the solar disk, creating a full halo, observed by the LASCO instrument of SOHO. A SPE (pfu~ 55 MeV) was measured on 4th April 2000. Solar wind plasma conditions, namely strongly negative and fluctuating IMF and high dynamic pressure in the sheath region behind the shock produced strongly driven magnetospheric activity. Several ionospheric activations occurred all around the auroral oval during the storm. Four of these activations, identified from the IMAGE data, showed substorm-like behavior (18:05, 20:13, 23:15, 00:30 UT, poleward and westward expansion of the night-side ionospheric current system, accompanied by particle injections observed at geostationary orbit in the midnight region) and were thus related to the release of the energy stored in the magnetotail. The cause of the increased energy storage during the storm was the strong driving caused by the negative B_z and the high pressure of the solar wind. Four other activations (17:08, 19:10, 20:55, 22:16 UT) were related to the expansion of the ionospheric current system but clear particle injections were missing.

16th July 2000 Severe Geomagnetic Storm

A CME on 14th July 2000 (10:54 UT) at heliographic position N17E01 measured from the NOAA region -AR 9077. This fast CME was associated with SF (X 5.7/3B) with expansion speed of around 2178 km s^{-1}, spreading all around the solar disk, creating a full halo, observed by the LASCO instrument of SOHO. A SPE (p.f.u.~ 24000 MeV) was measured on 14th April 2000. The plasma detector aboard ACE suffered a temporary black-out as a consequence of the flare accelerated particles. It consists of an interplanetary shock driven by a magnetic cloud, whose intense magnetic field (50 nT) rotates from south to north smoothly. While pointing southward, it causes a very intense fall in the D_{st} index, reaching its minimum of -300 nT

Study of Severe GMSs during SC-23

The severe GMSs are largely due to abnormal growth of rapidly decaying part in ring current. The severe GMSs have a direct effect to us and create many adverse effects within ionosphere and Earth's magnetosphere. Studies of severe GMSs are widely applicable in the field of space weather phenomena, satellite communications, navigation and power systems. We cannot stop these harmful GMSs any way but protect to our scientific systems on us by forecasting of them. The classifications of above mentioned large 90 GMSs with different D_{st} range are given as:

Types of GMSs	D_{st} range (nT)	Number of GMSs
Large GMSs	-150 to -100	61
Major GMSs	-250 to -151	18
Severe GMSs	< -250	11
	Total GMSs	**90**

Association of above 90 large GMSs with CMEs and coronal holes/coronal interaction regions (CIRs) presents that the 88% GMSs were caused by single/multiple CMEs, whereas, 12% were associated with CIRs. During solar cycle 23, 11 severe GMSs were observed. It is found that all severe GMSs are found to be associated with single/multiple halo CMEs and strong IP shocks. It is also found that maximum numbers of interplanetary shocks were caused by fast CMEs, which were responsible for producing large GMSs.

The Sun and Earth Connection

The Sun is source of energy, which sustains life on Earth. It gives steady warmth and light. The Sun affects the near Earth space and terrestrial atmosphere in a variety of ways. There are two kinds of processes by which it can affect the Earth's atmosphere namely, the high energy radiation and galactic particle emission. The formation of the ionosphere, density and plasma temperature are primarily depends on solar energy radiation especially from the extreme ultraviolet (EUV) and X-rays. The high energy radiation from the Sun in the form of EUV rays can destroy extreme conditions of solar activity. The coronal mass ejections (CMEs) are phenomena in which solar plasma material ejected from the corona in the form of charged particles. The more energetic components of these particles can damage the satellite communication as well as can be hazardous to astronauts. Apart from these, energetic particles manifest as aurora in the Polar Regions. It is now well believed that the solar magnetic field plays a major role in the production of high energy radiation and particles emissions. These strong beliefs follow from the observed enhancement in the high energy radiation and particle emission during solar activity. In this way; the solar magnetic field can be said to influence the Earth's weather and climate.

The Sun is the primary driver of space weather. Space weather occurs in the Sun's atmosphere, but may affect Earth's atmosphere. The basic components that influence the Earth's climatic system can occur externally (from extraterrestrial systems) and internally (from ocean, atmosphere and land systems). The external change may involve a variation in the Sun's output which would externally vary the amount of solar radiation received by the Earth's atmosphere and surface. Internal variations in the Earth's climatic system may be caused by changes in the concentrations of atmospheric gases, mountain building, volcanic activity, and changes in surface or atmospheric albedo.

Long-term Variation of Total Solar Irradiance (TSI)

The total solar irradiance (TSI) is integrated solar energy flux over the entire spectrum which arrives at the top of the atmosphere at the mean Sun-Earth distance. The TSI observations show variations ranging from a few days up to the 11-year SC and longer timescales [10]. The historical reconstruction of TSI absolute value is described by Kopp and Lean [11] based on new calibration and diagnostic measurements by using TIM V.12 data on 19th January 2012, and is updated annually. TSI are known to be linked to Earth climate and temperature. The historical reconstruction of TSI and their association with 11-year sunspot cycle from 1700 onwards are shown in Figure 4. From the plot, it is find that TSI variation trend follows with SSN within a limit but centurial variation trends of TSI have not shown clear association. Linear variation of TSI for last 311 years shows continuously increasing trend. It is find that decadal TSI variation trend follows with SSN within a limit, except Maunder Minimum period. The centurial variation trends of TSI have not shown clear association. Surface temperatures and solar activity both increased during the past 400 years, with close associations apparent in pre- and post-industrial epochs [12-13]. However, the inference from correlation studies that Sun-climate relationships can account for a substantial fraction of global warming in the past 150 years is controversial.

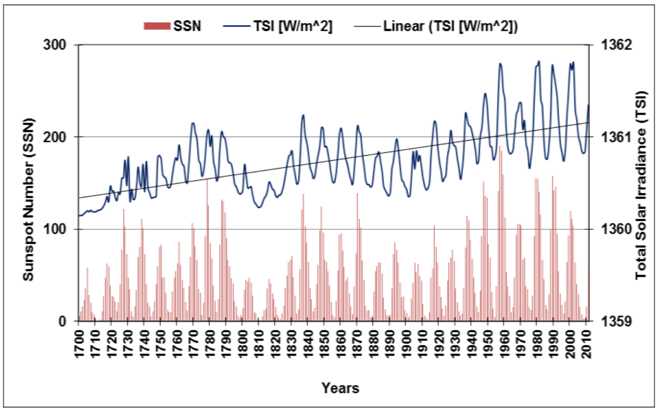

Fig 4. Long-term variation of TSI.

The Climate Change and Global Warming

The global warming is used to describe the changes of the large scale weather systems on Earth, and especially the surface temperature increase, by increase of atmospheric carbon dioxide (Co_2). The galactic cosmic rays increase the amount of C-14 in the atmospheric Co_2 and consequently, also in vegetation. During the increased solar activity close to solar cycle maximum years, Earth is better shielded from the cosmic rays than during the minimum years, and the amount of C-14 decreases. Thus the C-14 content of, for example, annual rings of old trees may reveal something about the Sun's performance during the last few millennia.

The amount of Co_2 that can be held in oceans is a function of temperature. The Co_2 is released from the oceans when global temperatures become warmer and diffuses into the ocean when temperatures are cooler. Initial changes in global temperature were triggered by changes in received solar radiation by the Earth through the Milankovitch cycles. The increase in Co_2 then amplified the global warming by enhancing the greenhouse effect. The long term climate changes represent a connection between the concentrations of Co_2 in the atmosphere and mean global temperature. The Co_2 is one of the more important gases responsible for the greenhouse effect. Certain atmospheric gases, like carbon dioxide, water vapor and methane, are able to alter the energy balance of the Earth by being able to absorb long wave radiation emitted from the Earth's surface. Without the greenhouse effect, the average global temperature of the Earth would be a cold -18° Celsius rather than the present 15° Celsius.

Human activities like the burning of fossil fuels, conversion of natural prairie to farmland, and deforestation have caused the release of Co_2 into the atmosphere. From the early 1700's, Co_2 has increased from 280 parts per million to 395 parts per million in present. The higher concentrations of Co_2 in the atmosphere will enhance the greenhouse effect making the planet warmer. A rise in global temperatures may boost the occurrence and concentration of severe climate events, such as floods, famines, heat waves, tornados, and twisters. Other consequences may comprise of higher or lower agricultural outputs, glacier melting, lesser summer stream flows, genus extinctions and rise in the ranges of disease vectors. As an effect of increase in global surface temperature species like golden toad, harlequin frog of Costa Rica has already become extinct. There are number of species that have a threat of disappearing soon and various new diseases have emerged lately. The increase in global surface temperature is extending the distribution of mosquitoes due to the increase in humidity levels and their frequent growth in warmer atmosphere. Various diseases due to ebola, hanta and machupo virus are expected due to warmer climates. The effect of increase in global surface temperature will definitely be seen on some species in the water.

The increase in global surface temperature is expected to cause irreversible changes in the ecosystem and the behavior of animals. Based on the study on past climate shifts and computer simulations, many climate scientists say that lacking of big curbs in greenhouse gas discharges, the 21st century might see temperatures rise of about 3 to 8º C, climate patterns piercingly shift, ice sheets contract and seas rise several feet. Climate change will exert unprecedented stress on the coastal and marine environment too. Increase in ocean temperature cause sea level rise and will have impact on ocean circulation patterns, ice cover, fresh water run-off, salinity, oxygen levels and water acidity. Sea level is rising around the world. In the last century, sea level rose 5 to 6 inches more than the global average along the Mid-Atlantic and Gulf Coasts, because coastal lands there are subsiding. Due to global warming, higher temperatures are expected to further raise sea level by expanding ocean water, melting mountain glaciers and small ice caps, and causing portions of Greenland and the Antarctic ice sheets to melt.

Forecasts of climate extremes can improve awareness and reduce adverse effects. Focusing attention on extreme events also may help countries to develop better means of dealing with the longer-term impacts of global climate change. Conversely, the pressures on the biosphere that drive climate change may cause critical thresholds to be breached, leading to shifts in natural systems that are unforeseen and rapid. Studying historical extremes of climate cannot forewarn on the consequences of such events. Rapid changes in climate during extreme events may be more stressful than slowly developing changes due to the greenhouse effect.

References

[1] C.T. Russell and R.L. McPherron, R. L., *Space Sci. Rev.*, 15, 1973, 205.
[2] W.D. Gonzalez, *Planet Space Sci.*, 38, 1990, 627.
[3] S.C. Dubey, *Indian J. of Radio and Space Phys*., 27, 1998, 43.
[4] S.C. Dubey and A.P. Mishra, *Earth Moon and Planet*, 84, 2000, 34.
[5] S.C. Dubey and A.P. Mishra, *Current Science*, 78, 2000, 1365.
[6] S.C. Dubey and A.P. Mishra, *Indian J. of Radio and Space Phys*., 29, 2000, 51.
[7] S.K. Pandey and S.C. Dubey, Indian J Radio Space Phys., 38, 2009, 305.
[8] M. Sugiura, *Ann. IGY*, 35, Part-I, 1964, 9-45.
[9] J. Kleczek, *Publ. Inst. Centr. Astron*., No. 22, 1952, Prague.
[10] M. Lockwood and C. Fröhlich, 2008, *Proc. Roy. Soc., Lond*., 2008.
[11] G. Kopp and J.L. Lean, 2011, *Geophys. Res. Letters Frontier article*, Vol. 38, 2011, L01706.
[12] J. Lean, J. Beer, and R. Bradley, *Geophys. Res. Lett*., 22, 1995, 3195.
[13] P.H. Reiff, T.W. Hill and J.L. Burch, *J. Geophys. Res*., 82, 1977, 479.