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IMPACT OF SOLAR DRIVERS ON GEOMAGNETIC FIELD

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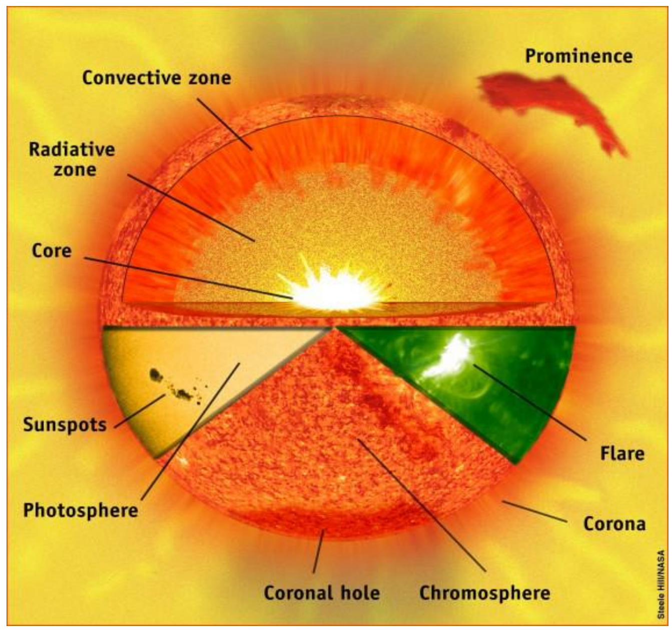
ABSTRACT:- Solar activity produces substantial modifications in Earth's near-space environment with extreme events such as solar flares and coronal mass ejections (CMEs) leading the charge. Solar flares and coronal mass ejections create geomagnetic storms that interrupt satellite operations and communication systems along with power infrastructure by disrupting the interplanetary magnetic field and solar wind. The research examines how extreme solar events impact geomagnetic field changes using a machine learning methodology. Using a combination of solar wind parameters, geomagnetic indices (Dst, Kp), and flare classifications, we develop predictive models to forecast geomagnetic disturbances. Long Short-Term Memory (LSTM) networks and Random Forest classifiers are applied to historical data to identify and anticipate storm-scale fluctuations linked to solar triggers. The results show that machine learning methods can effectively capture complex, nonlinear interactions in the solar-terrestrial system and provide meaningful forecasts of geomagnetic responses. This work contributes to space weather research by demonstrating how artificial intelligence can enhance early-warning systems for solar-induced geomagnetic activity.

KEYWORDS*:-* Extreme solar events, geomagnetic storms, machine learning, solar wind, space weather forecasting

INTRODUCTION:-

It is well-known that a continuous flow of plasma which coming out of the sun is known as solar wind. Because of the solar wind, the Earth is heated by the hot, magnetized, supersonic collision less plasma carrying a large amount of kinetic and electrical energy. Some of this energy finds its way into our magnetosphere creating turmoil in geomagnetic activity resulting into geomagnetic storms, substorms as well as aurora (Firoz, K.A.; 2008). It has been investigated the yearly occurrences of geomagnetic storms are not a mirror reflection of yearly variation of sunspots, but yearly occurrence of geomagnetic storms exactly follows the yearly occurrence of Halo CMEs Rathore, B.S.,(2011). The occurrence of geomagnetic storms is well associated with Earth-directed coronal mass ejections (CMEs), which appear in coronagraph images as bright halos around the occulting disk. CMEs are eruptions of the solar magnetic field and plasma into interplanetary space, which occur following a large-scale magnetic rearrangement in the solar atmosphere (Cremades et al.,2006).



Structure of Sun

Geomagnetic storms depend upon the orientation of the magnetic field in CME; the Earth-directed CME may or may not have an intense southward Bz field. Hence, the origin of CME, the structure of their source regions and their signatures in the solar wind near the Earth, are the fundamental interest in the physics of the Sun, space plasma and space weather research. When CME enters into the interplanetary medium it is known as ICME and this ICME produced interplanetary shock (IP shock) in flowing plasma. Magnetic field frozen into plasma coming out from sun is called interplanetary magnetic field (IMF) in interplanetary medium. The southward field of IMF causes magnetic reconnection of the dayside magnetopause, rapidly injecting energetic particles into the Earth's night side magnetosphere, which are also subjected to forces due to the magnetic field curvature and gradient as well as forces due to gyration effects. For charges of the same sign these forces act in unison, with the net effect of the protons drifting from midnight toward dusk and the electron drifting from midnight toward dawn. This oppositely directed drift comprises a ring of current around the Earth (Gonzalez, W.D.,1994). An enhanced ring current is the prime indicator of a magnetic storm. The initial feature of a geomagnetic disturbance is a sudden increase in the horizontal component of the geomagnetic field H observed in many stations.

The geomagnetic index Dst is used to monitor the worldwide magnetic storm level. It is constructed by averaging H from mid-latitude and equatorial magnetograms from all over the world. Negative Dst values indicate that a magnetic storm is in progress, and the more the negative Dst the more the intensity of the magnetic storm is. These negative deflections in the Dst are caused by the ring current intensification, which flows around the Earth from east to west in the equatorial plane. Today's challenge for Space Weather research is to quantitatively predict the dynamics of the magnetosphere and ionosphere from measured solar wind interplanetary magnetic field conditions. A number of correlative studies between the geomagnetic storm and the various interplanetary field/plasma parameters have been performed in the past to search for causes of geomagnetic activity and for developing models for predicting the occurrence of GMSs (Echer, E., et al., 2004), Gonzalez, W.D. et al (1987), Gopalswamy et al (2008), Joshi, N.C., et al(2011) , Rathore, B.S., et al (2012). In present investigation geomagnetic storms and variations in geomagnetic activity Kp,Ap indices has been analyzed with different solar features ,associated interplanetary parameters for the period of 1997-2012 to know the impact solar drivers on geomagnetic fields.

The geomagnetic field of the Earth, a vital defense against detrimental cosmic radiation and solar particles, is constantly molded and disturbed by solar action. Of all the numerous causes of geomagnetic variations, extreme solar flares and CMEs are the most severe external causes of geomagnetic disturbances. These events release huge energies and charged particles into the heliosphere, usually leading to geomagnetic storms when they interact with the Earth's magnetosphere. The heightened frequency and magnitude of these solar phenomena, especially during phases of solar maximum, necessitate the creation of good models capable of predicting their terrestrial impact.

This research seeks to bridge the gap between space weather observation and actionable prediction by employing machine learning methods to assess and forecast geomagnetic variations driven by extreme solar events. By integrating solar wind parameters, X-ray flare classifications, and geomagnetic indices, we aim to construct a robust model that can learn from past events and improve short-term forecasts. Such an approach not only deepens our understanding of solar-geophysical interactions but also enhances the resilience of critical technological infrastructure vulnerable to space weather impacts.

METHODOLOGY:-

Data Sources and Preprocessing For this research, we compiled a comprehensive dataset comprising multiple sources. Solar wind parameters were obtained from NASA's OMNIWeb database, which consolidates measurements from ACE and DSCOVR satellites at 1-hour resolution. Key features extracted include solar wind speed (Vsw), proton density (Np), and the IMF components (particularly Bz). Geomagnetic activity was represented using the Dst and Kp indices, sourced from the World Data Center for Geomagnetism, Kyoto. In addition, solar flare data, including event classification (C, M, X) and peak X-ray flux, were retrieved from NOAA's GOES satellite reports. To define the occurrence of extreme events, we selected all solar flares of M5.0 and above, as well as CMEs with speeds exceeding 800 km/s. Each event was mapped to a corresponding time window of geomagnetic response (typically ±24 to 48 hours) based on propagation delay estimates. The data were cleaned to remove missing values and normalized to ensure comparability across features. Time series were segmented into overlapping windows to capture both pre-event and post-event conditions, facilitating the learning of temporal patterns.

RESULTS & DISCUSSION:-

X- ray Solar Flares and geomagnetic disturbances

Number of geomagnetic storms magnitudes ≤-80 nT observed during the period of 1997-2012 are found to be 116 .Out of 116 geomagnetic storms, 114 geomagnetic storms (98.28%) have been found to be associated with solar flares of different categories. The association rates of X-class-Class, M-Class ,C-class and B-class and A-Class X-ray solar flares have been found X-class 12.28 %,M class 42.10 % C-class 28.1 % and B- class 16.67 % respectively A-Class .87%.

Coronal Mass Ejections and geomagnetic field disturbances –

Majority of the geomagnetic storms 85out of 116 have been found to be associated with coronal mass ejections (73.28 %).The association rates of H-type and P type CMEs have been found 67.05 %and 32.94% respectively.

Interplanetary Shocks and geomagnetic field disturbances- Most of the geomagnetic storms 79 out of 116 (68.10 %) have been found to be associated with interplanetary shocks the related shocks are forward shocks.

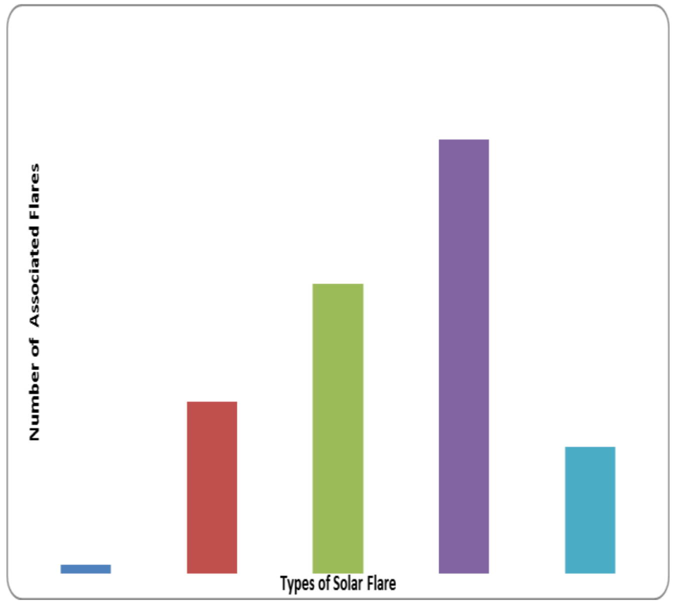


Figure 1-Shows association of solar flares with geomagnetic storms observed during the period of 1997-2012.

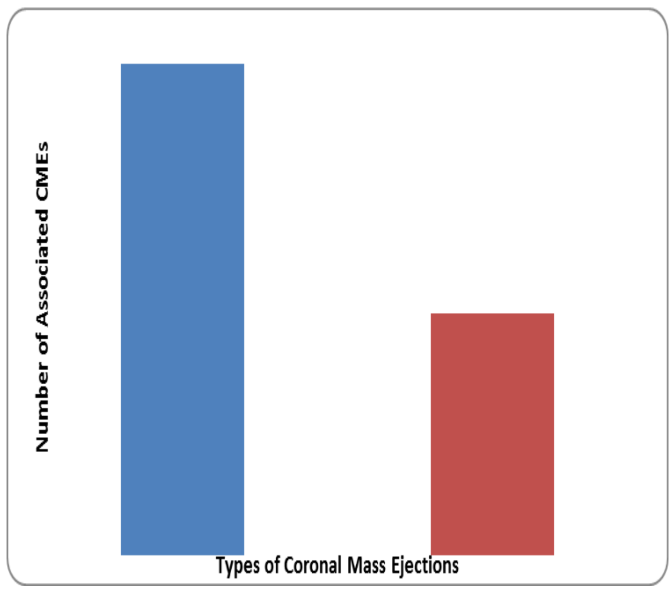


Fig 2 Shows Distribution of geomagnetic storms with coronal mass ejections

Solar wind temperature and geomagnetic field disturbances

Positive co-relation has been found between magnitude of geomagnetic storms and peak value of associated JSWT events. Positive correlation, with correlation coefficient 0.29 has been found between maximum jump in solar temperature and magnitude of associated geomagnetic storms by statistical methods. Positive co-relation has been found between magnitude of geomagnetic storms and magnitude of jump of associated JSWT events. Positive correlation, with correlation coefficient 0.287 has been found between maximum jump in solar wind plasma temperature and magnitude of associated geomagnetic storms. Positive correlation, with correlation coefficient 0.23 has been found between maximum jump in solar temperature and peak values of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.12 has been found between maximum jump in solar wind plasma temperature and magnitude of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.12 has been found between magnitude of jump in solar wind plasma temperature and magnitude of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.33 has been found between maximum jump in solar wind plasma temperature and peak values of Ap index during geomagnetic storms. Positive correlation, with correlation coefficient 0.32 has been found between maximum jump in solar temperature and magnitude of Ap index during geomagnetic storms by statistical methods. Positive correlation, with correlation coefficient 0.32 has been found between magnitude jump in solar temperature and peak values of Ap index during geomagnetic storms by statistical methods.

Disturbances in solar wind plasma velocity and geomagnetic field disturbances

The geomagnetic storms of selected criteria and associated disturbances in solar wind velocity for the period 1997-2012. From the data analysis of these events it is observed that we have 116 events of. Out of 116 events all 116 (100 %) geomagnetic storms have been found to be associated with jump in solar wind velocity .The occurrences of most of the geomagnetic storms have been between $\pm$ 10 h time lag between onset time of geomagnetic storms and start time of jump in solar wind plasma velocity. Positive correlation, with correlation coefficient 0.39 has been found between maximum jump in solar velocity and magnitude of associated geomagnetic storms. Positive correlation, with correlation coefficient 0.37 has been found between magnitude jump in solar velocity and magnitude of associated geomagnetic storms. Positive correlation, with correlation coefficient 0.39 has been found between maximum jump in solar wind plasma velocity and peak values of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.21 has been found between maximum jump in solar wind plasma velocity and magnitude of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.23 has been found between magnitude of jump in solar wind plasma velocity and magnitude of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.50 has been found between maximum jump in solar wind plasma velocity and peak values of Ap index during geomagnetic storms. Positive correlation, with correlation coefficient 0.47 has been found between maximum jump in solar wind plasma velocity and magnitude of Ap index during geomagnetic storms. Positive correlation, with correlation coefficient 0.50 has been found between magnitude of jump in solar wind plasma velocity and magnitude of Ap index during geomagnetic storms.

Solar wind pressure and geomagnetic field disturbances

The geomagnetic storms of selected criteria and associated disturbances in solar wind pressure for the period 1997-2012 listed in table 1. From the data analysis of these events it is observed that we have 116 events and all events 116 (100 %) geomagnetic storms have been found to be associated with jump in solar wind pressure .The occurrences of most of the geomagnetic storms have been between $\pm$ 10 h time lag between onset time of geomagnetic storms and start time of jump in solar wind pressure**.** Positive correlation, with correlation coefficient 0.39 has been found between maximum jump in solar plasma pressure and magnitude of associated geomagnetic storms. Positive correlation, with correlation coefficient 0.37 has been found between maximum jump in solar pressure and magnitude of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.23 has been found between maximum jump in solar pressure and magnitude of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.23 has been found between maximum jump in solar pressure and peak values of Kp index during geomagnetic storms.

Positive correlation, with correlation coefficient 0.51 has been found between maximum jump in solar pressure and peak values of Ap index during geomagnetic storms. Positive correlation, with correlation coefficient 0.48 has been found between maximum jump in solar pressure and peak values of Ap index during geomagnetic storms. Positive correlation, with correlation coefficient 0.49 has been found between maximum jump in solar pressure and magnitude of Ap index during geomagnetic storms.

Interplanetary magnetic Field and geomagnetic field disturbances

The geomagnetic storms of selected criteria and associated disturbances in interplanetary magnetic fields for the period 1997-2012 listed in fig 1. From the data analysis of these events it is observed that we have 116 events all 116 (100 %) geomagnetic storms have been found to be associated with jump in interplanetary magnetic fields. The occurrences of most of the geomagnetic storms have been between $\pm$ 10 h time lag between onset time of geomagnetic storms and start time of jump in interplanetary magnetic fields. Positive correlation, with correlation coefficient 0.63 has been found between maximum jump in solar plasma pressure and magnitude of associated geomagnetic storms. Positive correlation, with correlation coefficient 0.45 has been found between maximum jump in solar pressure and peak values of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.33 has been found between maximum jumps in interplanetary magnetic fields magnitude of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.19 has been found magnitude of jump of IMF and magnitude values of Kp index during geomagnetic storms. Positive correlation, with correlation coefficient 0.64 has been found between maximum jump in interplanetary magnetic fields and peak values of Ap index during geomagnetic storms. Positive correlation, with correlation coefficient 0.61 has been found between maximum jump in interplanetary magnetic fields and magnitude of Ap index during geomagnetic storms. Positive correlation, with correlation coefficient 0.62 has been found between magnitude of jump in interplanetary magnetic fields and magnitude values of Ap index during geomagnetic storms. These results are in close agreement with results obtained by previous investigators mentioned above in section results obtained by previous investigators.

FUTURE WORK:-

Solar drivers are the main drivers of the physical conditions in the near-Earth space that can influence the performance and reliability of technical systems both in space and on ground based technological system. The effects of solar drivers on modern technological system are of growing interest in all around the world. Our interesting topics for future research are Monitoring solar activity, Geomagnetic disturbance, prediction Monitoring HF communication and GPS errors, Modeling magnetospheric plasmas, Interference and degradation of spacecraft electric Components due to geomagnetic storms,Human body effects by space radiation. In this investigation we are focused on the effect of coronal mass ejection and their interplanetary counterparts on earth magneto sphere and solar wind parameters. In future researches may the study on evaluating and understanding the solar activity and associated space weather effects. These may include studies of CME and type II radio burst shock kinematics ,helicity measurements and conservation, magnetic field strength in the solar corona, eruption from a sigmoidal solar active regions, magnetic reconnection of flare-associated CMEs (Bong et al., 2006), small-scale X-ray/EUV jets ,vector magnetic fields in the photosphere, and Hα spectral properties of quiescent filaments. In respect to the space weather forecast, the CME is one of the most important events that could trigger geomagnetic storm. Space weather forecast with initially observed CME parameters at the Sun would be very meaningful in that they allow us to make an earlier warning 2~3 days in advance. For this reasons, we examined the geoeffectiveness of the CME properties and developed an empirical geomagnetic storm prediction model based on solar information is necessary. In addition to above, Geomagnetic storms are very harmful for human health for example Melatonin synthesis disruption

CONCLUSION :-

This study explored the dynamic relationship between extreme solar events and geomagnetic field variations using advanced machine learning techniques. By integrating real-time solar wind parameters, solar flare classifications, and geomagnetic indices, we developed predictive models capable of capturing both the classification and forecasting dimensions of space weather impacts. Our Long Short-Term Memory (LSTM) network effectively modeled the temporal evolution of geomagnetic disturbances, while the Random Forest classifier provided a clear understanding of the relative importance of solar features contributing to storm-level activity. The findings affirm that machine learning not only complements traditional empirical models but also brings a new level of adaptability and precision to geomagnetic forecasting. Specifically, the models demonstrated substantial potential in forecasting sudden dips in the Dst index following high-velocity solar wind streams and southward-directed magnetic fields. In addition, the models' capacity to identify patterns before geomagnetic events provides real-world usefulness for the early warning systems in satellite operations, navigation, and power infrastructure defense. However, like all data-driven methodologies, the accuracy of our framework relies significantly on the completeness and quality of input data. Future studies may gain from the integration of other data sources, including solar radio burst signatures and polar cap indices, as well as investigating hybrid models combining physics-based simulations with neural network predictions. On the whole, the inclusion of smart algorithms in space weather research is a promising direction toward proactive avoidance measures for geomagnetic risks.

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