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A Review of the Study of Solar Geomagnetic Storms During the Solar Cycle

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Abstract

Space weather, radio transmission, and satellite navigation all depend on the ionosphere, a dynamic region of the Earth's upper atmosphere. It is greatly impacted by solar activity, particularly when solar flares and coronal mass ejections generate geomagnetic disturbances. These solar disturbances cause geomagnetic storms that alter the distribution of ionospheric plasma in the Earth's magnetosphere. This study examines the ionosphere's response to geomagnetic storms during Solar Cycle 24. Geomagnetic storms that occurred during SolarCycle24areexaminedusingtheDst and Kp indices.Scientistsuse ionospheric measuressuchas Total Electron Content (TEC) and the critical frequency of the F2 layer (foF2) to learn how the ionosphere responds to variations in geomagnetic circumstances. Global satellite weather databases such as the International GNSS Service and the World Data Center for Geomagnetism provided the data used in this investigation. The study demonstratesthat significant variations in the ionospheric electron density and TEC values occurred during Solar Cycle 24 due togeomagnetic storms. There were bothpositiveand negative iono sphericstormphases, depending on how active the geomagnetic field was and how hot it was in the thermosphere. The results indicate a high correlation between ionospheric disruptions and the severity of geomagnetic storms. Even though Solar Cycle 24 wasn't as strong as past cycles, there were still severalstorms that had noticeable effects on the ionosphere. This research elucidates the interconnections

among solar activity, the magnetosphere, and the ionosphere. These research are important for making space weather predictions better and lessening the effects of ionospheric disruptions on satellite navigation and communication systems.

Key Words:

Magnetic Field, Radiation, Geomagnetic Storms, Coronal Mass Ejections (Cmes), Ionospheric

Introduction

The ionosphere is a part ofthe Earth's upper atmosphere that lets a lot ofsolar radiation through. It isbetween60 and 1000kilometersabovethe surface ofthe Earth.The major reasonit forms is because neutral air gases interact with sun radiation. The Sun's high-energy ultraviolet (UV) and X-ray radiation ionizes oxygen and nitrogen in the air, which makes amix of free electrons and ions. Radio wave propagation, satellite communication, and global navigation satellite systems (GNSS) alldependonthis ionizedatmosphere. The ionosphere isatremendouslyactiveareathat is affected by many things, like solar radiation, changes in the geomagnetic field, atmospheric tides, and solar wind disturbances. Solar activity is one ofthe most important things that affects the ionosphere's makeup and behavior. Solar cycles are changes in solar activity that happen every 11 years or so. Each solar cycle is marked by changes in the number of sunspots, solar flares, and coronal mass ejections (CMEs). Solar flares and coronal mass ejections are examples of solar disturbances that unleash huge amounts of energy and charged particles into space between planets. Geomagnetic storms result from the interaction of these powerful particles and plasma streams with Earth's magnetosphere. The dispersion of ionospheric plasma, which can alter the ionosphere's temperature, electron density, and structure, can be significantly impacted by these storms. The Earth's magnetic field and the interplanetary magnetic field (IMF) transported by the solar wind usually interact strongly to cause geomagnetic storms. Solar wind energy can enter the magnetosphere by magnetic reconnection at the magnetopause if the southbound portion of the IMF is powerful enough. Particles fall, the thermosphere warms, and electric fields intensify as a result of this energy transfer, all of which disrupt the ionospheric plasma. The ionosphere is frequently divided into three regions: D, E, and F, depending on how the electrons are

Figure1.1shows how solar wind affects the ionosphere and magnetosphere of Earth.

distributed. Because it contains the most electrons of all these layers, the F region—and especially the F2 layer—is crucial for long-distance radio transmission. During geomagnetic storms, the F2 layer is significantly impacted by variations in electric fields, thermospheric winds, and the neutral composition of the atmosphere. Positive ionospheric storms, which are characterized by higher electron density and totalelectron content (TEC), and negative ionospheric storms, whichare characterized bylower electrondensitydue to changes in the composition of the

atmosphere and more recombination processes, are the two main categories of ionospheric disturbances during geomagnetic storms. Satellite communication systems and navigation technologies maybe significantly impacted by these issues. For instance, by altering the Total Electron Content (TEC), geomagnetic storms can cause significant inaccuracies in radio signal transmission and GPS positioning. So, to improve space weather forecasting and cut down on tech problems, we need to know how the ionosphere reacts to geomagnetic storms.

One of the most important ways to study ionospheric variability is to look at Total Electron Content (TEC), which is the total number of electrons along a path between a satellite and a ground receiver. When geomagnetic conditions are not stable, TEC measurements taken from GPS

observations can tell us a lot about what is going on in the ionosphere. The solar cycle affects both the strength of solar activity and geomagnetic activity. Compared to previous solar cycles like Solar Cycle 23, Solar Cycle 24, which began in December 2008 and finished around

2019, was regarded as being a tad weak.

Despite being weaker, Solar Cycle 24

nevertheless produced some notable geomagnetic storms, particularly from 2012 to 2015. Studying how the ionosphere responds to geomagnetic disturbances was a great opportunity at this period. During Solar Cycle 24, numerous scientists observed significant shifts in ionospheric properties such as examining these occurrences. Measuring the strength of geomagnetic disturbances using geomagnetic indices such as the Dst, frequently located using the Dst index, which gauges the strength of the ring current surrounding Earth. While the Kp index indicatesthe activity of the geomagnetic field over the globe, the AE index indicates the activity of the auroral electrojet. Researchers can gain additional insight into the mechanisms causing ionospheric disruptions during storms by examining the relationship between these geomagnetic indices and ionospheric features. Examining how geomagnetic storms affect the ionosphere during Solar Cycle 24 is crucial for a number of reasons. First, it clarifies the relationship between space weather processes and various regions of near-Earth space. Second, when thesolarcycle isweak, it illustrateshow ionospheric plasma TEC, foF2(thecriticalfrequencyofthe F2 layer),andthedrift ratesofionosphericplasma. Fast-moving solar wind streams and coronal mass ejections, which resulted in geomagnetic storms, triggered these alterations. We can learn more about how the solar wind, magnetosphere, and ionosphere interact by Kp, and AE indices isacrucialaspectof geomagnetic storm research. Geomagnetic storms are respondsto solarperturbations.Finally, these investigations contribute to the development of more accurate models for forecasting the behavior of the ionosphere during geomagnetic storms. Global GPS networks, satellite observations,and ionosondedatahave made it possible forresearchersto examinechangesinthe ionospherewithgreat accuracyinbothspaceandtime. Scientistscaninvestigatethe mechanisms that lead to variations in electron densityand the ionosphere's dynamics during storms thanks to these observational techniques. By examining changes in ionospheric properties and their correlationwithgeomagneticactivityindices ,thisstudy seekstounderstandhowgeomagnetic storms affect the ionosphere throughout Solar Cycle 24. The findings of the study will improve knowledge of ionospheric disruptions and how they affect communication and navigation systems.

Methodology

The impact ofgeomagnetic stormsonthe ionosphere during Solar Cycle 24 is investigated using several space-weather and ionospheric datasets. To determine the strength of a geomagnetic storm, we utilize standard geomagnetic indices from global space-weather datasets.

1. TheDst(DisturbanceStormTime)Indexmeasureshowstrongtheringcurrentis surrounding Earth. It is often used to sort geomagnetic storms.
2. The Kp Index shows how active the Earth's magnetic field is around the world ona scale from 0 to 9.
3. TheAEIndexshowshowactivetheauroralelectrojetisandgivesinformationabout disturbances in the magnetosphere.

Tthese numbers from the National Oceanic and Atmospheric Administration's space weather database and the World Data Center for Geomagnetism.

IonosphereData

To study ionospheric disruptions during geomagnetic storms, we get ionospheric parameters from:

1. TotalElectronContent (TEC)datafromGPS
2. Measurements fromanionosonde
3. Observationsfromsatellites

The InternationalGNSS Service collects TEC dataand makesworldwide ionospheric TEC maps from GPS data.

SolarActivity

The National Aeronautics and Space Administration and the NOAA Space Weather Prediction Center keep track of solar parameters like the amount of sunspots, the speed of the solar wind, and the magnetic field between planets.

Thesedatasetsassistfindsolarevents like:

1. Flaresfromthe sun
2. CoronalMassEjections (CMEs)
3. Fast-movingstreamsofsolar wind

GeomagneticStormEvents

The Dst index is used to find geomagnetic storms that happened during Solar Cycle

24. The current studyfocusesonsignificant geomagneticstormsthattranspired from2008to 2019.The following are the several levels of storm intensity:

StormCategory	**Dst Value**
Weakstorm	-30nTto-50nT
Moderatestorm	-50nTto-100nT
Intensestorm	<-100nT

Researchers look at these vents to learn more a boutionospheric disruptions.

1. GeomagneticStorminMarch2013
2. GeomagneticStorminJune2015
3. GeomagneticStorminSeptember2017

ParametersoftheIonospherethatwerestudieddur ingstorms,thefollowingionospheric parameters are looked at:

Total Electron Content: - TEC represents the total number of electrons along the path between a satellite and ground receiver.

TECiscalculatedas:

$$TEC=\int N_e ds$$

Where:

N_e=electrondensity

ds=pathlengthalongthesignal

TE Cvariationsindicate changesinionosphericplasmadensityduringgeo magneticstorms.

CriticalFrequency(foF2)

The **foF2** parameter represents the maximum plasma frequency of the F2 layer and is related to the peak electron density of the ionosphere.

$$f_oF_2=9\sqrt{N_{max}}$$

Where:

N_{max}=maximumelectrondensityintheF2layer

ChangesinfoF2duringgeomagneticstormsprovi deimportantinformation aboutionospheric disturbances.

Electron Density

Electron density variations are studied to understand the structure and dynamics of the ionospheric plasma during disturbed geomagnetic conditions. The following analytical techniques are used in the study:

Storm-Time Analysis

Ionospheric parameters are analyzed before, during, and after geomagnetic storm events to determine storm-time disturbances.

QuietDayComparison

Ionospheric parameters during storm periods are compared withquiet geomagnetic conditions to determine the magnitude of disturbances.

Statistical Analysis

Statistical methods are used to examine there relationship between:

1. Geomagnetic indices (Dst,Kp)
2. Ionospheric parameters(TEC, foF2)

The study's over all procedure involves several steps to find out how geomagnetic storms affected the ionospheric area during Solar Cycle24. First, reliable space weather data bases are used to get information about geomagnetic storms that happen during this solar cycle. The Dst (Disturbance Storm Time) index is often used to measure how bad geomagnetic storms are. It is then used to find and sort these storm events. After finding the storm periods, we get ionospheric parameters like Total Electron Content (TEC) andthecriticalfrequencyoftheF2 layer (foF2) for the chosen events from international ionospheric observation systems. These include the International GNSS Service and the World Data Center for Geomagnetism. To observe how the ionosphere changes during storms, a number of factors are examined. The ionospheric conditions on geomagnetically disturbed days are compared with those on geomagnetically calm days in order to ascertain the size and nature of disturbances during storms. The connection between geomagnetic activity indices and ionospheric reactionsis also examine during statistical analysis. In order to identify significant ionospheric changes that occur during geomagnetic storms and to gain a better understanding of how the ionosphere operates during adverse space weather, the gathered data is finally analyzed.

Discussion

The structure and behavior of the ionosphere are greatly impacted by solar disturbances, according to an examination of geomagnetic storm events during Solar Cycle 24. The Earth's magnetosphere receives a lot of energy and charged particles when solar activity is strong, such as during solar flares and coronal mass ejections. This results in geomagnetic storms that alter the distribution of ionospheric plasma. Strong geomagnetic storms are associated with significant changes in ionospheric electron density and Total Electron Content (TEC), according to the findings of examining geomagnetic indices and ionospheric features. Storms cause the Dst index to drop significantly, indicating that the magnetosphere's ring current is most likely more active. Significant variations in TEC values and the critical frequency(foF2) of the F2 layer correspond with this disturbance. In many storm events examined during Solar Cycle 24, the ionosphere displayed both positive and negative storm phases. TEC values increased significantly during the positive phase due to increased ionization and vertical plasma drift brought on by storm-time electric fields. The early and primary phases of geomagnetic storms are whenthis rise in electron density is most often seen. However, in the last phases of the storm, there was often a negative ionospheric phase. Because the thermosphere's composition shifts and recombination processes quicken, this phase is identified by a decrease in electron density and TEC values. As additional molecules, like nitrogen, combine with one another, the density of ionospheric plasma decreases. Geomagnetic activity and ionospheric disturbances are clearly related, according to a statistical analysis of geomagnetic indices and ionospheric characteristics. TEC and foF2 levels often fluctuate more during severe geomagnetic storms. This suggests that the ionosphere is greatly impacted by interactions between the solar wind and the magnetosphere. The findings also demonstrate that ionospheric disruptions vary by time and place. Numerous factors, including as the ionosphere's condition, the season, the location on Earth, and the time of day, all contribute to changes. During storms, plasma may ascend due to thermospheric winds and electric fields, which may transport ionospheric plasma to higher latitudes and altitudes. Even though Solar Cycle 24 was predicted to be weaker than previous cycles, several powerful geomagnetic storms that caused ionospheric disturbances were never the less seen. The sevents provided significant

Insights into the mechanics of interaction among the Sun, magnetosphere, and ionosphere. All things considered, the variations in TEC and electron densitythat were seen during geomagnetic storms show how important it is to study how the ionosphere reacts to solar disturbances. This kind of research is very important for learning more about space weather and how it affects modern technology systems.

Summary

There search advances our knowledge of the inter play between solar activity, the magnetosphere, and the ionosphere. 7. 7. Understanding how the ionosphere acts during storms is essential for using GPS navigation, satellite communication, and space weather forecasting. The analysis of geomagnetic storm events during Solar Cycle 24 leads to the following conclusions:

1. Ionospheric measurements such as electrondensity, fo F2, and total electron content (TEC)are significantly impacted by geomagnetic storms.

2. Ionospheric disruptions and geomagnetic activity indices(Dst,Kp) are strongly correlated during storms.

3. Complex ionosphericresponseswerediscovere dbythe monitoring of both positive and negative ionospheric storm phases during geomagnetic disturbances.

4. The ionosphere's characteristics may be altered by a variety of factors, including local time, geographic location, and storm intensity.

5. Although Solar Cycle24 was relatively moderate,the ionosphere had significant issues due to many geomagnetic storms.

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