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An Investigation into the Geomagnetic and Ionospheric Response During a Magnetic Activity at High and Mid-Latitute

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Abstract: In this research, researchers have presented a geomagnetic and ionospheric response to solar wind activity of the geomagnetic storm of April 14, 2006. The indicators used in this research; foF2, Dst, Bz and flow speed implies an intense storm in the perturbation of both the earth's magnetic field and the peak electron density of the F2 layer and these perturbation in turn could affect global communication given that intense storms could occur simultaneously across the globe. It was also noted that the time the enhancement was observed at the Ionospheric stations corresponds to the point when the Bz experiences a northward orientation. Also at this time, the Dst began to reduce to its peak minimum value as well as the intensification of the ring current as indicated by the flow speed plot. All these points to the fact that the southward turning of Bz may have been accompanied by an increase in solar wind dynamic pressure which may have led to an enhanced coupling between the solar wind and the terrestrial magnetosphere that significantly increased the geoeffectiveness of the solar wind. Moreover, the average ionospheric electron content enhancement observed at the high latitude stations of Petrropalvosk, Magadan and the mid-latitude stations of Khabarovsk and Tashkent between the hours of 0800 UT and 1200 UUT could be attributed to the response of the charged particles to the neutral atmosphere in the thermosphere which automatically produces waves and changes in the thermospheric winds and composition. On the overall, the storm event could be regarded as a negative phase one.

Key words: Thermospheric winds, flow speed, ionospheric electron content, magnetosphere, Earth's magnetic field

INTRODUCTION

It is extremely important to understand geomagnetic storms because of the effects they have on life on earth. A geomagnetic storm is a marked temporary disturbance of the earth's magnetic field. It was discovered by Baron Alexander von Humboldt and a colleague from May, 1806 until June, 1807 when they observed local Berlin magnetic declination every half hour from midnight to morning. They used a microscope to identify which direction the magnetic needle was pointing. On December 21, 1806, strong magnetic disturbances were recorded. Humboldt noted that this magnetic disturbance was accompanied by strong aurora lights. In the morning, the aurora was gone, the magnetic disturbances were gone and they were left with the discovery of geomagnetic storm. It was initially thought that geomagnetic storms were produced by the influx of a greater than normal amount of solar particles released from the sun during a flare or Coronal Mass Ejection (CME). However, solar flares and Coronal Mass Ejection (CME) are related to geomagnetic storms but not because of the increase influx of particles into the earth's magnetosphere. Dal-Lago *et al*. (2004) defines geomagnetic storms as intervals of time when a sufficiently intense and long lasting interplanetary convention 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 index (Fig. 1).

Geomagnetic storms are major disturbances of the magnetosphere that occur when the interplanetary magnetic field turns southward and remain southward for a prolonged time. The turning of the interplanetary field to the northward direction restores it to its pre-storm state. Magnetic storm starts with a sudden increase of the intensity of the geomagnetic field horizontal component, called SSC (from Storm Sudden Commencement).

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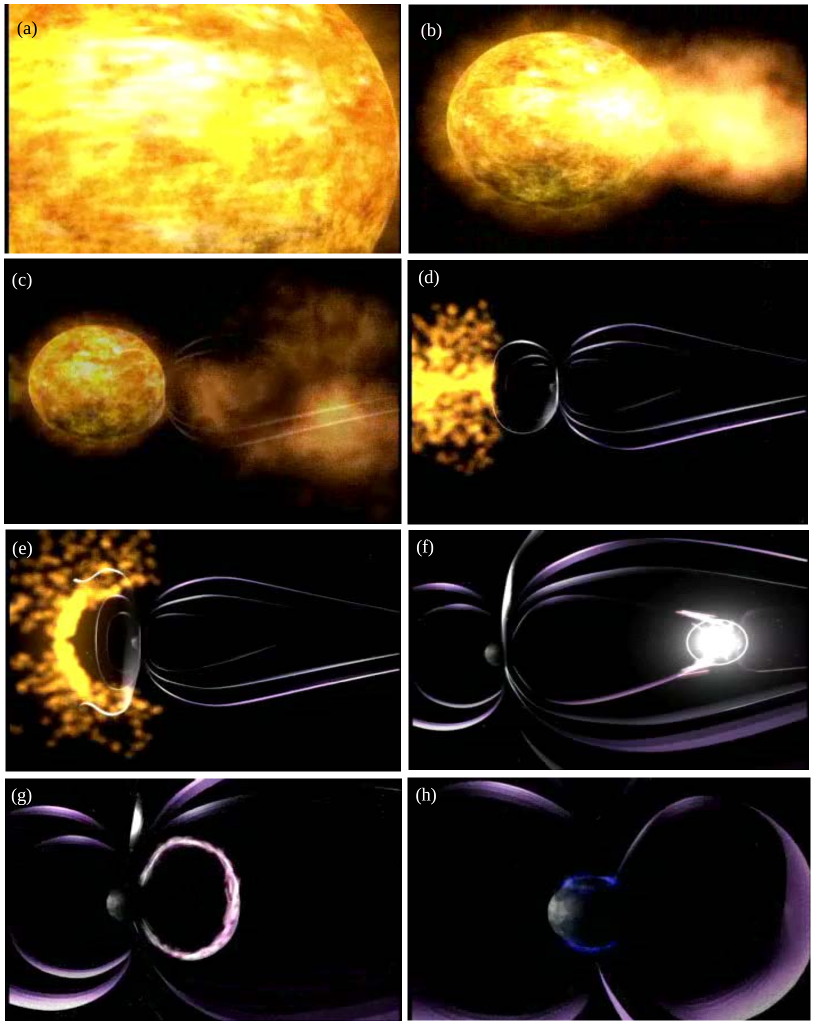

Fig. 1: a, b) The progressive stages of the sun's outburst of ejecta; c, d) the action of the fast moving solar wind from the sun on the magnetosphere; e, f) The CMEs effect on the ring current; g, h) Finally the effect on the earth causing magnetic storms

Basically, the southward interplanetary magnetic field causes magnetic reconnection in the dayside magnetopause, rapidly injecting magnetic and particle energy into the earth's magnetosphere and modifying the large-scale ring current systems. Reconnection leads to a number of phenomena: aurora, geomagnetic storms and enhanced ring currents.

Many recent studies have shown that the magnitudes and different phases of the geomagnetic storm depend upon solar wind speed, Interplanetary Magnetic Field (IMF) magnitude and the presence of large Southward interplanetary field (IMF) Bz.

Magnetic activity indices were designed to describe variation in the geomagnetic field caused by these irregular current systems. However, there are several areas where electromagnetic interference affects communication systems. However, the vulnerability of wireless communication links from sources of this interference is on the increase.

The increase in the number of transmission systems, band congestion and international interference activities posed a significant threat to the normal operation, availability and reliability of these wireless systems.

This study is therefore, aimed at exploring the geomagnetic storm of April 14, 2006 (which is one of the natural phenomena affecting telecommunication industries through interference) by making a thorough investigation into the interplanetary, geomagnetic and ionospheric phenomenon associated with the storm.

MATERIALS AND METHODS

Data available are the measured parameter of solar wind plasma for the period of April 12-16, 2006; Dst (nT), flow speed (km sec^{-1}) and the imbedded Interplanetary Magnetic Field (IMF) Bz (nT) associated with the storm of April 14, 2006. The component is particularly considered because according to Gonzalez and Tsurutani (1987), the IMF structures leading to intense magnetic storms have an intense and long duration of southward component. Such a configuration tends to increase the coupling between the solar wind and the magnetosphere with the result that relatively more solar wind energy can enter the magnetosphere (Lal, 2000). These data are hourly observations obtained from the National Geophysical Data Centers SPIDR OMNI IMF data (http//spdr.ngdc. noaa.gov).

Moreover, the ionospheric data used in this study consists of hourly values of foF2 obtained from some of the National Geophysical Data Centers SPIDR (Space Physics Integrative Data Research Source) global network of ionosonde stations. These stations are located in Asian sector of the world. The data span between April 12-16, 2006 and consists of hourly values of f_0F2 where f_0F2 is the F2 ionospheric response of the magnetic storm. The stations are shown in Table 1. The study is concerned with variations in f_0F2 due to the geomagnetic storm of April 12-16, 2006 at Asia Sector stations of the world. However, the F2 region response to geomagnetic storms is most conveniently described in terms of Df_0F2 the normalized deviations of the critical frequency f_0F2 from the reference:

$$D(f_0F2) = [f_0F2-(f_0F2)ave]/(f_0F2)\ ave \qquad (1)$$

Hence, the analyzed data consists of the Df_0F2 of respective hourly values of f_0F2 on April 14. The reference for each hour is the average value f_0F2 for that hour calculated from the 3 quiet days, April 12-16, 2006 following the storm. The use of D (foF2), the normalized deviations of the critical frequency rather than the critical frequency itself provides a first-order correction for temporal, seasonal and solar cycle variations.

Table 1: Ionosonde stations

Stations	Geographic co-ordinates
Petropalvosk	62.4°N, 137.2°E
Podkamneya	61.6°N, 162.0°E
Magadan	60.0°N, 151.0°E
Tomsk	56.5°N, 132.0°E
Novosibirk	52.4°N, 139.8°E
Khabarovsk	48.5°N, 135.1°E
Tashkent	41.3°N, 141.7°E

RESULTS AND DISCUSSION

Interplanetary and geomagnetic observations: Figure 2 shows the interplanetary and geomagnetic observations. From the first panel indicating the low-latitude magnetic index Dst. It was observed that there was a build up of magnetic activity up till around 14.00 UT of April 13 indicating the presence of a magnetic shock in the interplanetary medium. Before this time, there was no significance disorder in the F2 region of the ionosphere. However, at exactly 09.00 UT of April 14, the Dst recorded its maximum depression value of -111nT indicating an intense, single phase storm. It thereafter began recovery through April 16.

From the second panel of the same figure showing the embedded Interplanetary Magnetic Field (IMF) along the z axis (Bz), it was observed that the instance the Dst is about to decrease to its minimum peak value at around 00.00 UT on April 14 coincides with the point at which the Bz rotates southwardly from its original northward orientation. The Bz recorded its minimum peak value around 07.00 UT on April 14 to a value of -14.0nT. Thus, in the interplanetary region following CIR, the southward field components caused by the magnetic waves can cause magnetic reconnection, small injections of plasma into the magnetosphere and prolonged recovery phases of the storms. According to Gonzalez and Tsurutani (1987), events of this type are known as high intensity long duration, continuous AE activity (HILDCAA) events. It should be noted that the IMF structures leading to intense magnetic storms have intense (>10nT) and long duration (>3 h) Southward component. Note that the Bz experienced a Southward turning whose southward duration is >3 h and having a value of -14.0nT. According to Kane (2005), the duration for which Bz is negative is important factor in the relationship of solar and interplanetary plasma parameters with geomagnetic storms.

The flow speed (or solar wind speed) plot [third panel of Fig. 2 shows the existence of a slow stream in the period 00.00 UT April 12 with Vsw <450 km sec^{-1} till 14.00 UT on April 13. It thereafter begins to rise throughout the recovery stage through April 16 to a value above 500 km sec^{-1}. According to Gonzalez *et al.* (2002) intense magnetic storms (Dst<-100nT) occur when the solar wind speed is substantially higher than the average speed of Vsw equals 400 km sec^{-1}. It was also argued by Adebesin in his research roles of interplanetary and geomagnetic parameters in intense and very intense magnetic storms generation and their geoeffectiveness that all very intense storms are likely to have a plasma flow speed >550 km sec^{-1} within the storm interval but not

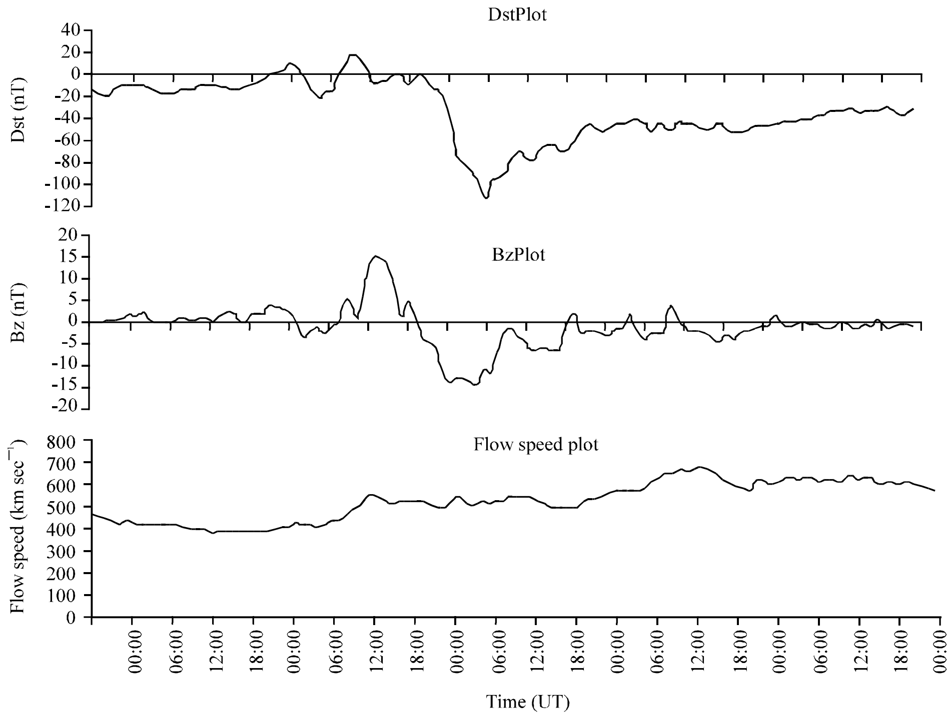

Fig. 2: Interplanetary and geomagnetic observations for April 12-14, 2006

all flow speed >550 km sec^{-1} are very intense storms of which the present flow speed value agrees with (i.e., minimum peak Dst value of -111nT) Gosling *et al.* (1991) and Taylor *et al.* (1994) have also shown that there are varieties of ejecta speeds but it has been statistically shown that the ones that are most effective in creating magnetic storms are events that are fast with speeds exceeding the ambient wind speed by the magnetosonic wave speed, thereby causing a fast forward shock.

Ionospheric response: The plot of the deviation of the critical frequency [i.e., D (foF2) plot] for the Asian sector is as shown in Fig. 3a and b. The ionospheric stations under analysis include three high latitude stations of Petropalvosk (62.4°N), Podkamneya (61.6°N) and Magadan (60.0°N) as well as four mid-latitude stations of Tomsk (56.5°N), Novosibirk (52.4°N), Khabarovsk (48.5°N) and Taskent (41.3°N).

The stations are classified based on their latitudinal positions. High latitude stations are stations whose latitudinal position values are ≥58.5°N while mid-latitudes are between the value range of 20.0 and 58.0°N. The D (foF2) plot is for 5 days spanning 12-16 April, 2006 representing 2 days before the storm, the storm day and 2 days after the storm (storm recovery days). It should be noted that an appreciable change from the rest position (from the 0.00 level on the y-axis) up to a value >0.50 is indicative of action of geomagnetic storm in such a station [either below the zero point (depression) or above it (enhancement)]. The F layer critical frequency foF2 is used because of its direct relationship with the F layer peak electron density NmF2 (which is a measure of positive or negative storm effects through its significant increases or decreases about the mean position, respectively):

$$\text{foF2 (Hz)} = 9.0 \times \sqrt{[\text{NmF2}]}\ (\text{m}^{-3}) \quad (2)$$

From the first panel of Fig. 3a, reflecting the plot of the high latitude station of Petropalvosk, it was observed that there is no immediate effect on foF2 following sudden commencement. However, by around 09.00 UT of April 14, an enhancement of foF2 became obvious reaching a value of above 0.50. It thereafter began to deplete from this point forward and throughout the remaining days on the plot.

The same pattern was observed at the mid-latitude station of Khabarovsk (second panel) as well as the high latitude station of Tashkent (fourth panel). It should be noted that the instance the enhancement was observed at these three Ionospheric stations corresponds to the point when the Bz (second panel of Fig. 2) experiences a

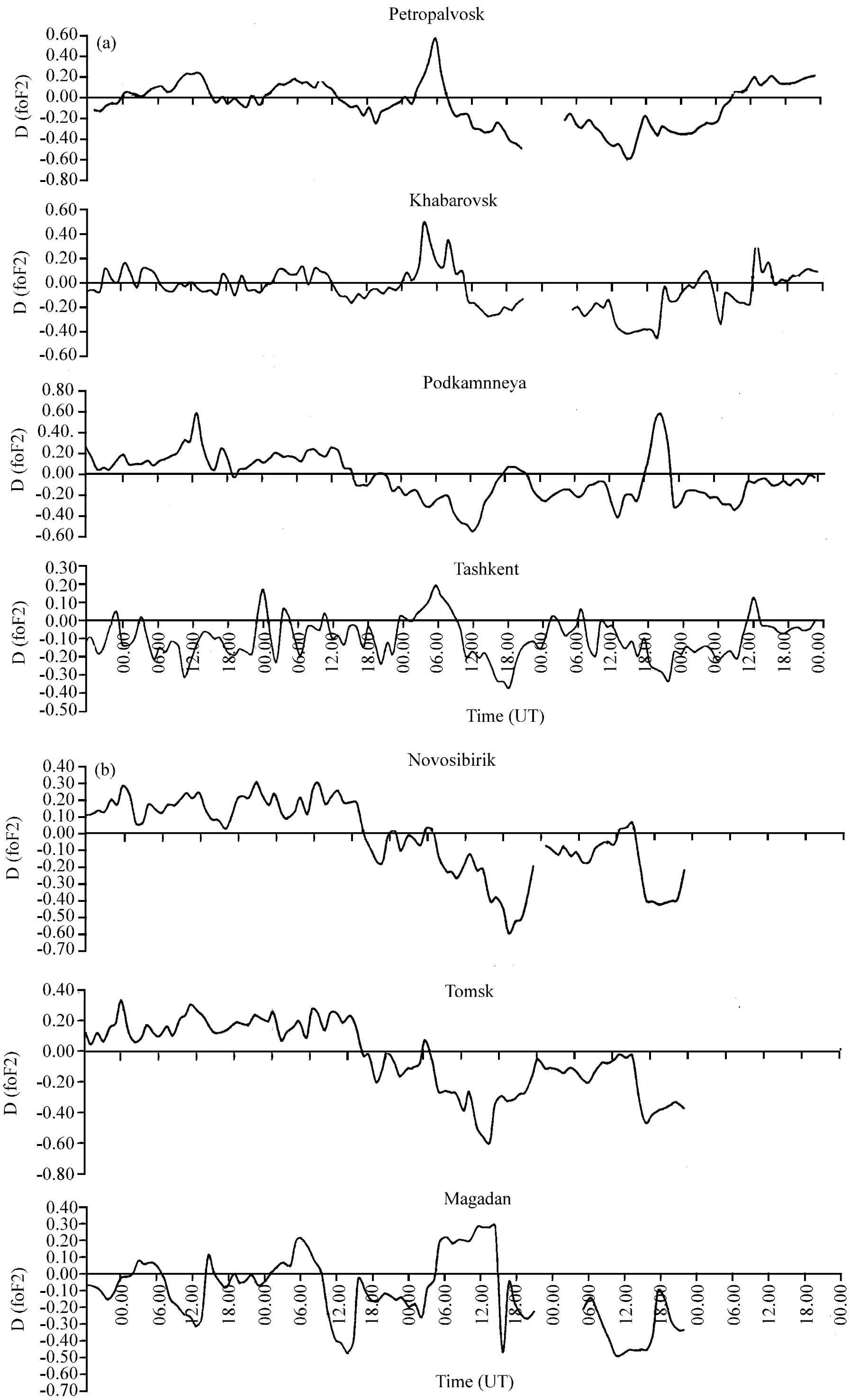

Fig. 3: a) Variation in D (foF2) in Asian Sector during the storm of 12-16 April, 2006; b) Variation in D (foF2) in Asian Sector during the storm of 12-16 April, 2006

Northward orientation, the Dst (first panel of Fig. 2) began to reduce to its minimum peak value as well as the intensification of the ring current, as seen on the flow speed plot of Fig. 2. All these points to the fact that the southward turning of Bz may have been accompanied by an increase in solar wind dynamic pressure which may have led to an enhanced coupling between the solar wind and the terrestrial magnetosphere that significantly increased the geoeffectiveness of the solar wind (Chukwuma, 2007).

According to Adebesin there are a variety of causes of Southward IMFs in the high speed stream sheath region. Firstly, if there is a preexisting southward component upstream of the shock, shock compression will intensify this component. As these fields convect towards the driver gas region, the drapping effect will intensify the fields further for the earth's magnetosheath fields. Turbulent waves and discontinuities can also be associated with strong northward and southward IMFs.

However, the appearance of the positive phase storms at the high latitude stations under investigation is as a result of energy being injected into the polar upper atmosphere as the solar wind become geoeffective which in turn launches a Traveling Atmospheric Disturbance (TAD) which propagates with high velocity (Danilov, 2001).

This TAD carries along equatorward-directed winds of moderate magnitude. At high latitudes, these meridonial winds drive ionization up inclines magnetic field lines and cause uplifting of the F layer, leading to an increase in the ionization density positive storm. The Ionospheric response plot at Podkamnneya (third panel of Fig. 3a, Novosibirk (first panel of Fig. 3b, Tomsk 3(b) second panel) and high latitude station of Magadan (last panel) reflects more of a negative phase storm. These observed decrease in foF2 during the storm is related to the neutral composition disturbances. Heating at auroral and high latitudes causes expansion of the neutral atmosphere and enhanced neutral winds carry disturbed composition. However, enhancement in the mean molecular mass in the neutral composition disturbance zone leads to an increase in the loss rate of ions, resulting in a decrease of the ionospheric plasma density and thus a negative storm. Strickland *et al*. (2001) had shown that negative ionospheric storm effects are indeed correlated with the region of enhanced molecular mass.

The complex processes of interaction between the ionospheric plasma and the neutral gas was studied by Chandra and Stubble (1971) by solving a couple of systems of ionospheric and atmospheric equations. Their calculations showed that a decrease in $[O]/[N_2]$ in the lower thermosphere as a result of the change in turbopause level, triggers a complex chain of reactions in the ionospheric system. However, Seaton (1956) introduced the concept of the change in neutral composition during magnetic storms and suggested that an enhancement in $[O_2]$ at the F region altitudes may result from an increase in the turbopause altitude caused by increasing mixing in the lower thermosphere.

The ionosphere varies greatly because of changes in two sources of ionization and it responds to changes in the neutral part of the upper atmosphere in which it is embedded. This region of the atmosphere is known as the thermosphere since it responds to solar EUV radiation, the ionosphere varies over the 24 h period between daytime and night time and over the 11 years solar cycle of solar density. On shorter time scales, solar X-ray radiation can increase dramatically when a solar flares occurs. This increase the D and E regions ionization. During a geomagnetic storm, the auroral source of ionization becomes much more intense and variable and expands to lower latitudes. The other main sources of variability in the ionosphere come from charged particles responding to the neutral atmosphere in the thermosphere. The ionosphere responds to the thermospheric winds: they can push the ionosphere along the inclined magnetic field lines to different latitude.

The ionosphere responds to the composition of the thermosphere which affects the rate that ions and electrons recombine during a geomagnetic storm, the energy input at high latitudes produces waves and changes in thermospheric winds and composition. This produces both the observed increases (positive phase) and decreases (negative phase) in the electron concentration. The Interplanetary Magnetic Field (IMF) is a vector quantity with three dimensional components, two out of these components are Bx and By which are oriented parallel to the ecliptic. The third component Bz is perpendicular to the ecliptic and is created by waves and other disturbances in the solar wind. When the Interplanetary Magnetic Field (IMF) and geomagnetic field lines are oriented opposite or anti-parallel to each other they can merge or reconnect resulting in the transfer of energy, mass and momentum from the solar wind flow to magnetosphere.

The strongest coupling with the most dramatic magnetosphere effects occurs when the Bz component is oriented southward. The North-South component Bz plays a dominant role in determining the amount of solar wind energy to be transferred to the magnetosphere to produce geomagnetic storm. However, the F2 layer is often profoundly affected during the magnetic storms with severe effects on radio propagation. At mid-latitudes the F2 layer electron density initially increases then often decrease during the storms main phase and recovers in 2-3 days. The geomagnetic storm is the most important phenomenon in the complex chain of solar terrestrial relations and space weather. The storm is triggered by solar wind energy, captured by the magnetosphere and transferred and dissipated in the high-latitude ionosphere and atmosphere (Prolss, 1995). These periods of increased energy deposition set up complicated changes in the complex morphology of the electric temperature winds and composition and affect all ionospheric parameters. One of the main characteristics of the disturbed ionosphere is a great degree of variability which we have experienced in this study.

Due to many interacting factors, each storm shows a different course. Sometimes, this individual course departs markedly from the general pattern. The response of the ionospheric F2 region to magnetospheric disturbances is different from that of the lower ionosphere. The difference is due to the differences in physical mechanisms responsible for the changes of the electron concentration /e/. While in the E and D regions the primary reason of the /e/ changes is the variation of the ionization rate because of corpuscular intrusions, there is no considerable change of the ionizing source density in the F2 region during geomagnetic disturbances and so the electron concentration variations are due to indirect factors such as changes in neutral composition and dynamical processes (Danilov, 2001). It should also be noted that one of the significant features of the negative phase is its equator shift during the storm from auroral latitudes to middle latitudes. In most cases, the negative phases demonstrate a well-pronounced dependence on the intensity of the magnetic disturbance as expressed by various geomagnetic indices.

However, positive phase sometimes are observed several hours before the beginning of the magnetic disturbance which caused this particular ionospheric storm (Danilov, 2001). All these features are important for understanding the physical mechanisms operating in the ionosphere during magnetic disturbances. While negative phases are almost always observed at high latitudes and nearly as positive phases at middle latitudes. Geomagnetic activity as we know is a measure of the energy which the geomagnetic field intercepts from the passing solar wind and funnels into the magnetosphere. Solar wind energy, besides heating the upper atmosphere also seems to ionize principally the topmost F2 layer of the ionosphere which becomes a region of transition and interaction between the ionospheric and magnetospheric plasmas (Lal, 2000). Because of this unique position, the variation of the peak electron density of the F2 layer appears to acquire the signature of the impact of the solar wind. The terrestrial implication of these is that the very rapid field change during a magnetic storm induce current in the earth and are easily channelled through conducting material within the earth. This current is referred to as Geomagnetically Induce Current (GIC).

Researchers have therefore presented a geomagnetic and ionospheric response to solar wind on the Geomagnetic storm of April 14, 2006; the indicators used being foF2, Dst, Bz and flow speed implies an intense storm in the perturbation of both the Earth's magnetic field and the peak electron density of the F2 layer and these perturbation in turn could affect global communication given that intense storms could occur simultaneously across the globe. Moreover, the average Ionospheric electron content enhancement observed at the high latitude stations of Petrropalvosk, Magadan and the mid-latitude stations of Khabarovsk and Tashkent between the hours of 0800 UT and 1200 UUT could be attributed to the response of the charged particles to the neutral atmosphere in the thermosphere which automatically produces waves and changes in the thermospheric winds and composition.

CONCLUSION

According to the results of this study, the storm event could be regarded as a negative phase one.

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