SHOCK-INDUCED TRANSIENT VARIATIONS IN THE POLAR CUSP IONOSPHERE

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ABSTRACT

On June 16, 2012, an interplanetary (IP) shock caused by the solar wind compressed Earth's magnetosphere and triggered electromagnetic disturbances in the polar ionosphere. This study investigates the ionospheric response and driving factors following the IP shock. Observations revealed vertical plasma drift along with horizontal motion, and SuperDARN radar data showed a reversal in ionospheric convection. This reversal disrupted the existing shear equilibrium, suggesting that the IP shock-induced electric field led to enhanced velocity shear mapped to the E region. The dusk-to-dawn electric field during the preliminary phase of the sudden impulse (SI) explained the horizontal plasma motion. Additionally, the convection reversal was driven by downward field-aligned currents. For the first time, this study identifies the immediate and direct response of the cusp ionosphere to the IP shock, which is essential for understanding the global magnetospheric response to sudden changes in the interplanetary magnetic field (IMF) and solar wind conditions.

INTRODUCTION

Interplanetary shocks and dynamic pressure (Pdyn) fluctuations in the solar wind strongly influence the Earth's magnetosphere and plasma convection (Boudouridis, 2007). When an IP shock reaches the magnetosphere, it compresses the magnetopause, intensifying the dawnward flowing current (Araki, 1994). As a result, an abrupt increase in the horizontal component of the magnetic field is observed at mid and low latitudes, known as a Sudden Impulse (SI).

During this interaction, magnetic disturbances observed at high latitudes are more complex due to various physical processes (Kikuchi, 1986). IP shocks also intensify magnetic reconnection on the dayside magnetopause and in the nightside magnetotail (Boudouridis, 2007). Depending on the magnetosphere-ionosphere system, the IP shock can cause significant changes in the ionosphere.

Satellite and ground-based GPS observations show that in equatorial and mid-latitude regions, the total electron content (TEC) increases significantly, rising above 430 km during the daytime (Tsurutani, 2004; Amarjargal, 2019).

The goal of this study is to investigate the immediate changes in horizontal plasma convection in the polar cap ionosphere caused by a sudden change in the solar wind driven IP shock. Using SuperDARN radar data from the southern polar region (Zhongshan - ZHO and McMurdo - MCM stations), we constructed convection models during the period ~09–11 UT on June 16, 2012.

DATA ANALYSIS

In this section, we examine the observations obtained from the digisonde and SuperDARN radars on June 16, 2012. As a first step, we conducted a detailed analysis of the solar wind conditions using data from the GOES and WIND satellites, and investigated their impacts on Earth's magnetic field. We also analyzed ground-based station data from locations ranging from the equator to high latitudes.

RESULTS AND DISCUSSION

The SYM-H geomagnetic activity index indicates that the approaching IP shock front reached the magnetopause at 09:56 UT during the daytime, suggesting that the IP shock observed by the WIND satellite at 09:02 UT took approximately 54 minutes to propagate to near-Earth space. This shock was also detected at the Ulaanbaatar geomagnetic observatory (ULN) at 09:56 UT, as shown in Figure 1. As a result of the IP shock, the current on the dayside magnetopause intensified in the eastward direction, producing a typical sudden impulse (SI), as evidenced by the SYM-H index. The vertical dashed line in the figure marks the onset of the SI event.

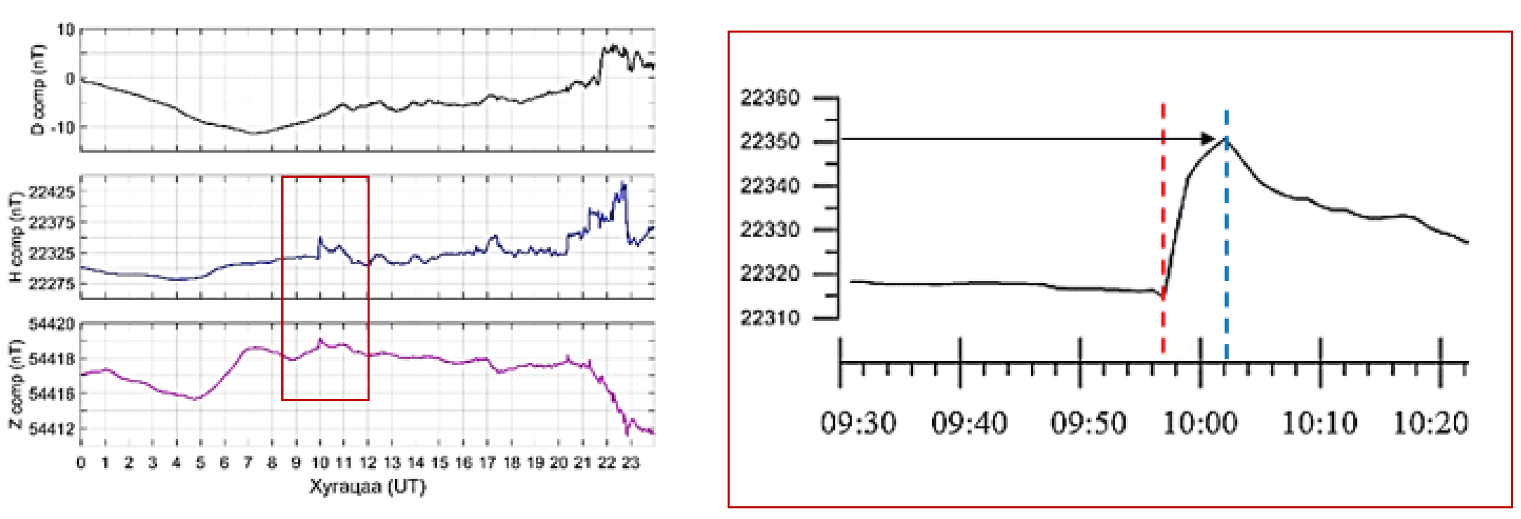


Figure 1

SOLAR WIND AND INTERMAGNET DATA

The WIND satellite, located between the Sun and the Earth, was positioned at a distance of approximately (227 RE, –99 RE, 20 RE) in the GSM coordinate system. Measurements of the interplanetary magnetic field (IMF) and solar wind plasma parameters from WIND and GOES satellites during the time interval 08:00 UT to 10:00 UT are shown in Figure 2. The first three panels of the figure present the IMF components (B, Bx – northward, By – dawnward, Bz – vertical). Prior to 09:02 UT, the IMF remained relatively stable, indicating a steady interplanetary environment. However, beginning at 09:02 UT, a sudden and sharp change in the interplanetary magnetic field was observed. The vertical component Bz, which had been fluctuating near zero, suddenly increased in magnitude. Such abrupt variations in the By and Bz components contributed to an increase in the total magnetic field strength (B).

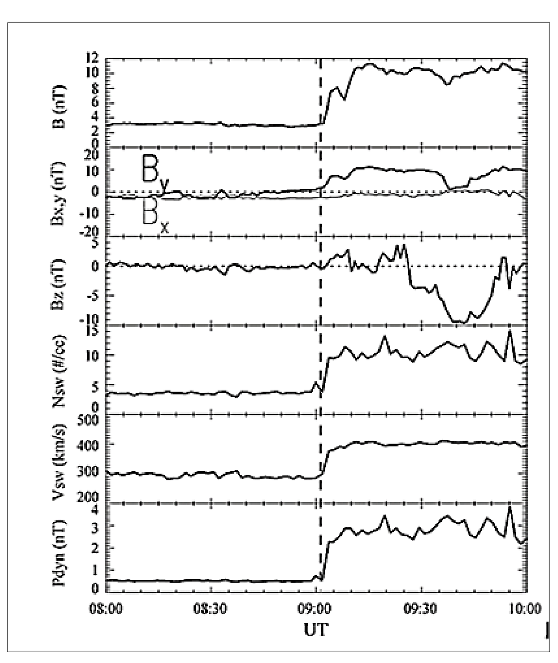


Figure 2

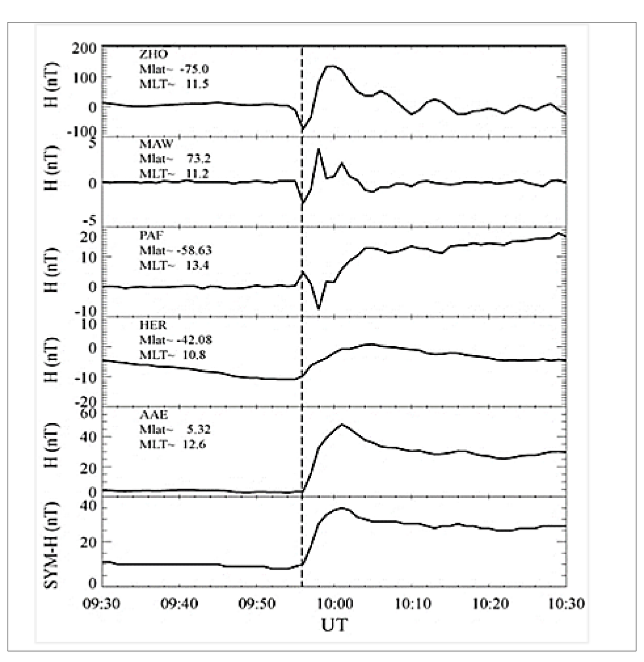


Figure 3

The solar wind density (Nsw), solar wind speed (Vsw), and dynamic pressure (Pdyn) are shown in Figur 2.

At 09:02 UT, the solar wind plasma parameters were relatively stable, with a low density of Nsw = 4–11 particles/cm³ and a plasma speed of Vsw ≈ 300 km/s. According to WIND satellite data, at approximately 09:02 UT, the density changed from Nsw = 4 to 11 particles/cm³ and the speed increased from Vsw = 300 km/s to 400 km/s, indicating a noticeable variation. As a result of changes in these two plasma parameters, the solar wind dynamic pressure (Pdyn) immediately increased from ~0.5 nPa to ~3 nPa, as marked by the vertical dashed line in Figure 2.

To assess the effects of the IP shock wave, we examined the horizontal component of the geomagnetic field and the SYM-H geomagnetic activity index during the same time interval (09:30 UT–10:30 UT) at geomagnetic observatories located at different geographic positions. In Figure 3, several geomagnetic observatories from different latitudes were selected and arranged in order of decreasing geomagnetic latitude from high to low latitudes.

The geographic latitudes of the selected observatories are also shown in the Figure 3.

Data from magnetometers at the observatories AAE and that the horizontal components in the low latitudes of the Southern Hemisphere exhibit a stepwise increase. Therefore, although the onset time of the geomagnetic variations is nearly simultaneous across all stations, the amplitude of the magnetic field response varies from location to location.

At the high latitudes, ground based measurements at PAF show an initial positive impulse followed by a negative one. In contrast, magnetometer data from other high-latitude locations (e.g., ZHO and MAW) reveal more complex disturbances in Earth's magnetic field: a slight initial decrease followed by a sharp increase in intensity near magnetic local noon.

RADAR

The horizontal drift of ionospheric plasma (convection phenomenon) was determined using SuperDARN radar observations. The observations from the SuperDARN ZHO and MCM radars are presented, showing variations in line-of-sight Doppler measurements. During the sudden impulse (SI) event, the ZHO radar has the advantage of monitoring convection flows in the dayside polar cusp region between 12:00 and 14:00 MLT, while the MCM radar shows both sunward and anti-sunward measurement results. The representative beams of these two radars, mentioned in the top-left of the figure, are shown using range-time-intensity (RTI) plots of the line-of-sight (LoS) Doppler velocity. In Figure 9, the Doppler velocity is color-coded by the scale on the right-hand side, indicating plasma flows directed toward the radar site (blue shift) and away from it (red shift), respectively.

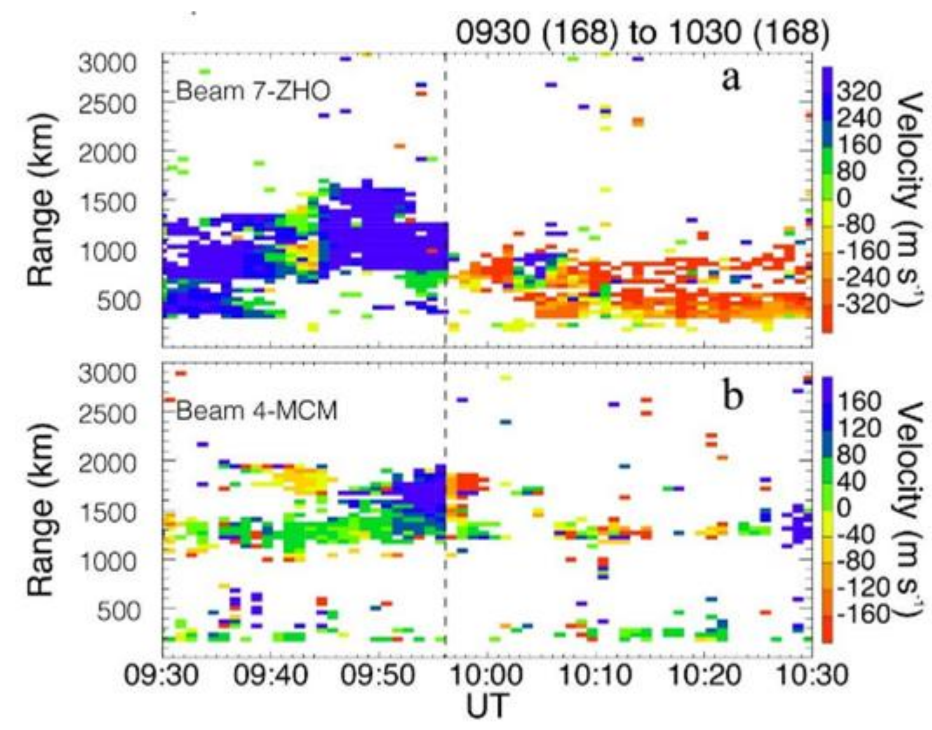
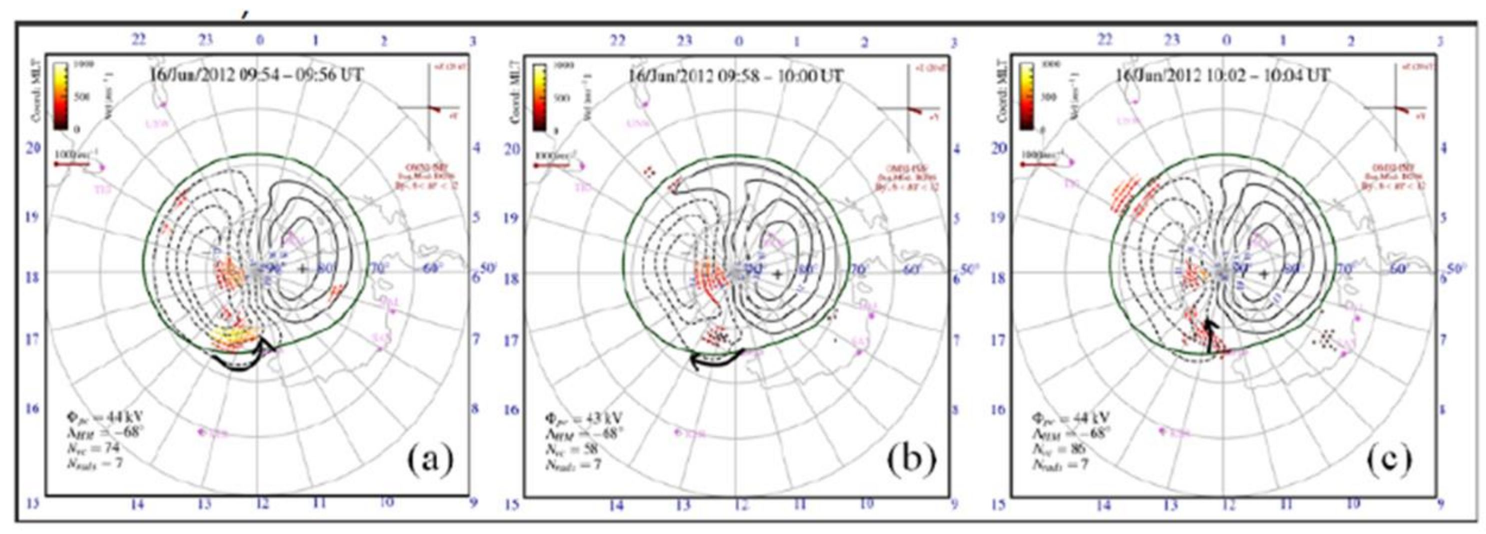


Figure 7

CONCLUSION

This research work investigated the impact of an interplanetary (IP) shock wave on the polar ionosphere on June 16, 2012. The IP shock wave compressed the Earth's magnetosphere, leading to significant changes in the electromagnetic field of the polar ionosphere. The observations from Radar Network detected anticonvective flow in the ionosphere. The study identified a high-energy particle flow entering the ionosphere, which was associated with sudden impulse (SI) movement. Furthermore, the counter-convective flow observed in the ionosphere was attributed to eddy currents. These findings emphasize the direct and rapid influence of IP shock waves on the ionosphere and the subsequent modification of the Earth's magnetosphere following sudden changes in the interplanetary magnetic field (IMF).



We observe sudden changes in both the magnitude and direction of the LoS (line-of-sight) Doppler velocity from the two radars. Before the arrival of the IP shock wave (indicated by the vertical dashed line), the ZHO radar detected strong LoS plasma motion directed toward the ZHO station, with speeds exceeding 800 m/s, indicating the typical westward return flow in the convection throat region around magnetic local noon (12 MLT).

However, following the arrival of the IP shock driven by the fast forward IP shock front, the LoS Doppler velocity abruptly reversed direction from westward to eastward. This reverse flow lasted for approximately 6 minutes, from 09:56 UT to 10:02 UT, and the convection flow remained directed eastward during this interval. Similarly, the ionospheric plasma flow measured by the SuperDARN MCM radar also shows a reversed flow. After the sudden onset, the plasma flow—particularly the unsteady behavior—briefly switches from an anti-sunward direction to a sunward direction.

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