Optical and SuperDARN signature associated with the negative SI

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Introduction

Transient magnetospheric phenomena and their relationship to conditions in the solar wind are very important for the study of the energy transfer process between the solar wind and Earth's magnetosphere. It has long been known that sudden positive changes in solar wind dynamic pressure trigger the geomagnetic sudden commencement (SC) or positive sudden impulse (SI^+). The ground level magnetic field shows systematic variations with latitude and local time that reflect the transmission of complex signals through the magnetosphere and the earth-ionosphere waveguide (Araki, 1994; Engebretson et al., 1999). It is also known that solar wind dynamic pressure variations drive magnetopause motion, magnetospheric magnetic field compression, ground magnetic pulsations (Kaufmann and Walker, 1974), ULF/VLF plasma wave activity (Hirasawa, 1981) and cosmic noise absorption. Optical auroral enhancement also occurs associated with SCs (Vorobyev, 1974; Craven et al., 1986; Zhou and Tsurutani, 1999).

The geomagnetic response to a sudden expansion of the magnetosphere is called negative geomagnetic sudden impulse (SI^-). Although SCs have been analyzed by many investigators, detailed analyses of SI^-s have not been made except by Araki and Nagano (1988), and to our knowledge no report on their relationship to the optical aurora has been made. The purpose of this paper is to report the response of the optical/radar/particle auroras and magnetic variations associated with a solar wind negative pressure impulse. The data used in this study were acquired by the WIND and GEOTAIL satellites in the solar wind, by the low-altitude DMSP-F13 satellite, by SuperDARN HF radars over the northern and southern polar regions, by the ground-based magnetometers in the polar region and at lower latitudes, and by the all-sky TV imager at Zhongshan Station in Antarctica (74.49 degrees S invariant magnetic latitude).

Observations

The WIND satellite was at (79.7, -60.2, -14.8) R_E in GSE coordinates. A dramatic drop in solar wind electron density and ion dynamic pressure from 23 to 7 cm^{-3} and 11 to 2 nPa, respectively occurred at 1350 UT. The dynamic pressure of 11 nPa and 2 nPa corresponds to extremely high and average solar wind density, respectively (Slavin and Holzer, 1981; Sibeck et al., 1991). At the same time, the interplanetary magnetic field (IMF) changed suddenly with its magnitude (B_T) increasing from 11 to 14 nT, the B_Y component increasing from -5 to 3 nT and the B_Z component decreasing from -2 to -10 nT, respectively. These changes occurred within a time interval of about 2 minutes. On the other hand, the solar wind speed was about 450 km/s and did not show significant impulsive changes during the passage of the plasma discontinuity.

The GEOTAIL satellite was located at about (6.5, 14.7, 0.1) R_E in the GSE coordinates at 1438 UT when the solar wind discontinuity was observed. B_T, B_Y, B_Z and the solar wind speed suddenly changed from 10 to 40 nT, -3 to 15 nT, -2 to -30 nT, and 440 to 250 km/s, respectively. This position is very close to the average location of the bow shock, though the real location of the bow shock depends on the solar wind conditions (Slavin and Holzer, 1981; Bennett et al., 1997). The observational data showed that the IMF and solar wind plasma observations at the two spacecraft were very similar prior to the discontinuity arrival at the location of GEOTAIL. This feature indicates that GEOTAIL was upstream of the bow shock. After the discontinuity passage GEOTAIL measurements were quite different from those at WIND indicating that the GEOTAIL was now immersed in the magnetosheath (see for example the reduction in the plasma velocity noted above). Consequently, these features indicate that the bow shock suddenly expanded in association with the passage of the solar wind negative pressure impulse, and it is reasonable to assume that the magnetopause also expanded as the discontinuity propagated through the magnetosheath to the magnetopause.

The Keogram was reproduced from all-sky TV images at Zhongshan, together with the H component (geomagnetic N-S direction) of magnetogram observed at Zhongshan and the X component (geographic N-S direction) of Bear Island (BJN) in the northern hemisphere. The geomagnetic latitude of BJN is about 71.3 degrees, and is located about 3 degrees lower in latitude than that of the geomagnetically conjugate point of Zhongshan. The magnetic local time (MLT) at 1430 UT corresponds to 1550 MLT at Zhongshan. It is found that three cycles of quasi-periodic luminosity pulsations were observed during the time interval of 1430-1510 UT. The centers of three main luminosity enhancements appeared to be separated by about 10-14 min. The first luminosity pulsation enhanced at about 1435 UT, and the enhanced region moved poleward during 1437-1440 UT. When the poleward-moving aurora reached their luminosity maximum, a new, faint aurora appeared at the poleward side of the zenith at about 1439 UT. Then the new aurora gradually moved equatorward until about 1443 UT. The second and the third cycles of the luminosity pulsations appeared at about 1445 UT and 1456 UT, respectively, drifting equatorward of their average position. We interpret the poleward motion as due to the sudden expansion of the magnetopause caused by the negative solar wind pressure impulse, and the equatorward shift as be due to the erosion of the magnetopause caused by the sudden southward turning of IMF B_Z.

It is also found that the variations of the H component were very similar to the luminosity variations of the optical aurora during the time interval of about 1432 UT-1445 UT at Zhongshan and 1432 UT-1510 UT at BJN. The timing of the intensity maximum of the magnetic variation is the same as that of the auroral luminosity maximum; the first magnetic pulse at Zhongshan is coincident with the first optical enhancement. The next optical enhancement shows little magnetic signature at Zhongshan and the third none. This is likely because the pulsation activity has moved equatorward of Zhongshan, in the same manner as the optical aurora. At Bear Island, which is slightly equatorward of the conjugate point of Zhongshan, the pulsation activity is apparent for all three optical enhancements. These observations suggest that there is a close relationship between the generation of the luminosity pulsations and the magnetic pulsations.

It was fortuitous that the low-altitude DMSP-F13 satellite traversed almost directly over the Zhongshan at about 1436:30 UT when the optical auroral enhancement was observed. The energy flux of precipitating electrons and the magnetic variations observed by DMSP-F13 showed that Inverted 'V' like electron precipitation with an energy peak of a few-keV were observed at about 1436:30 UT, at the same position of the discrete aurora observed from the all-sky TV imager at Zhongshan. These characteristics suggest that the discrete auroras are generated via field-aligned acceleration processes in the magnetosphere. It is also found that a pair of upward and downward field-aligned currents were observed between 1436:20 UT (~75 MLAT) and 1437:40 UT (~72 MLAT), in agreement with the afternoon sector statistical pattern reported by Iijima and Potemra (1976). However, the electron population inside and outside the inverted 'V' structure is very cold (approx. 150 eV); there is very little evidence of electrons from the central plasma sheet and boundary plasma sheet as are typically seen in the Region 1 / Region 2 current system. It is notable that the location of the discrete aurora corresponds to the region of the intense upward field-aligned current. Further more, the DMSP-F13 visible image data (not shown here) demonstrated that a discrete aurora with a scale size of more than 3000 km was extending in the east-west direction along the auroral oval. The visible image data did not show spatially periodic auroral features as reported by Liu et al., (1989). These observations suggest that a large scale east-west-aligned discrete aurora, which is associated with the accelerated electron precipitation and the upward field-aligned current, was triggered by the magnetic disturbances in the magnetosphere which is due to the sudden expansion of the magnetopause caused by the solar wind negative pressure impulse.

The backscatter HF power observed by the CUTLASS Iceland East HF radar showed that the backscatter suddenly enhanced at 1438-1440 UT during the full 16 beam scans. Then the backscatter power kept with some intensity levels until 1446-1448 UT. It is notable that the time interval of 1438-1440 UT corresponds to the period when the optical aurora and magnetic pulsation observed at Zhongshan reached their intensity maximum. The line of site Doppler velocity showed that the direction of the convection velocity was eastward in the region between 70 to 75 degree of magnetic latitude, and that was westward in the region of 75-80 degrees. It is interesting that the location of the convection reversal moved to poleward with time from 1438 UT to 1448 UT. Such poleward motion of the convection reversal was also found by Stokkseyri Iceland West HF radar. We can interpret that the poleward movement of the convection reversal would be caused by the effect of the magnetopause expansion associated with the solar wind negative pressure impulse. The spatial relationship between the optical aurora at Zhongshan and the CUTLASS HF radar backscatter showed that the optical aurora was located at the region of the minimum power of the HF backscatter region.

The IMAGE magnetometer network is aligned near the geomagnetic meridian of Zhongshan, and the nominal geomagnetically conjugate point of Zhongshan is located between HOR (Hornsund; 74.02 degrees in magnetic latitude) and LYR (Longyearbyen; 75.12 degrees). A positive excursion of the X component of magnetic variations was observed at about 1432 UT at the auroral zone observatories (SOR, MUD, and PEL). Such signatures are the same as the Araki and Nagano (1988) SI^- model in the afternoon sector in the auroral zone. This timing of the pulsation is almost the same as that at the Kakioka low-latitude observatory as shown in Figure 1b. We examine here the relationship between the three cycles of luminosity pulsations at Zhongshan as shown in Figure 2 and the magnetic pulsations observed by the IMAGE magnetometer network. As mentioned above, the magnetic pulsations at BJN correlate with the luminosity pulsations, so we examine here the relationship between the magnetogram at BJN and other magnetograms.

The first cycle of the magnetic pulsations appeared at almost all observatories, and the pulsation amplitude became a maximum at HOR and BJN. The amplitude at the two observatories was about 2-4 times larger than that at the observatories in the higher latitude regions (LYR and NAL) and also in the lower latitude regions. A phase lag was observed between BJN and NAL. A similar small phase lag also occurred between NUR and SOR. These pulsations had the characteristic features of a field-line resonance (FLR), with a latitudinally narrow peak in power, accompanied by a latitudinal phase shift (Walker et al., 1979). For the second cycle of the pulsations, the BJN magnetogram showed good correlation with the pulsation at the lower latitude observatories located between SOR and NOR. On the other hand, higher latitude magnetograms (HOR, LYR, and NAL) showed poor correlation with that at BJN. The third cycle of the pulsations appeared only at BJN. It is notable that the magnetic variations observed at Zhongshan better fit HOR than LYR and/or other observatories. These features suggest that the true conjugate point of Zhongshan was located near HOR during the time interval of our interest.

Discussion and Conclusion

The important results in this event are that the optical auroras were associated with the SI^-. The interesting problem is why and how a rarefaction of the magnetopause acts to trigger the optical auroral enhancement. This observation is the opposite of what one would expect from standard theories in which auroral features increase or are initiated by increased pressure but not decreased pressure. For example Zhou and Tsurutani (1999) recently proposed a model that the solar wind plasma compression (SC) leads to the loss cone instability, wave-particle interactions, and concomitant particle loss into the ionosphere. If we apply their model to the negative solar wind pressure impulse, no enhancement of optical aurora would be expected, because the rarefaction of the magnetosphere acts to restrain the loss cone instability.

The important features observed by the ground-based all-sky imager and magnetogram and by the low-altitude DMSP satellite are that the discrete optical aurora is closely related to the magnetic pulsations with the characteristic features of a field-line resonance, the inverted 'V' like precipitating of cold electrons, the upward field-aligned current, and the HF radar back scatter. These observations show that the solar wind negative pressure impulse triggered a field-line resonance of the geomagnetic field. The resonance caused the upward and downward field-aligned current sheets, field-aligned electron acceleration, and HF radar irregularities in the ionosphere via dynamic coupling processes between the solar wind, magnetosphere, and ionosphere.

References

Araki, T., and H. Nagano, Geomagnetic response to sudden expansions of the magnetosphere, J. Geophys. Res., 93, 3983-3988, 1988.

Araki, T., A physical model of the geomagnetic sudden commencement, in Solar Wind Sources of Magnetospheric Ultra-Low Frequency Waves, Geophys Monograph, vol. 81, edited by M J. Engebretson, K. Takahashi, and M. Scoler, pp. 183-200, AGU, Washington, D. C., 1994.

Bennett, L., M. G. Kivelson, K. K. Khurana, L. A. Frank, and W. R. Paterson, A model of the Earth distant bow shock, J. Geophys. Res., 102, 26927-26941, 1997.

Craven, J. D., L. A. Frank, C. T. Russell, E. J. Smith and R. P. Lepping, Global auroral responses to magnetospheric compressions by shocks in the solar wind: two case studies, in Solar Wind-Magnetosphere Coupling, edited by Y. Kamide and J. A, Slavin, pp. 367-380, Terra Scientific, Tokyo, 1986.

Engebretson, M. J., D. L. Murr, W. J. Hughes, H. Luhr, T. Moretto, J. L. Posch, A. T. Weatherwax. T. J. Rosenberg, C. G. Maclennan, L. J. Lanzerotti, F. Marcucci, S. Dennis, G. Burns, J. Bitterly, and M. Bitterly, A multipoint determination of the propagation velocity of a sudden commencement across the polar ionosphere, J. Geophys. Res., 104, 22,433-22,451, 1999.

Hirasawa, T., Effects of magnetospheric compression and expansion on spectral structure of ULF emissions, Mem. Natl. Inst. Polar Res., 18, 127-151, 1981.

Iijima, T., and T. A. Potemra, Field-aligned currents in the dayside cusp observed by Triad, J. Geophys. Res., 81, 5971-5979, 1976.

Kaufmann, R. L., and D, N. Walker, Hydromagnetic waves excited during an SSC, J. Geophys. Res., 79, 5187-5195, 1974.

Lui, A. T. Y., D. Venkatesan, and J. S. Murphree, Auroral bright spots on the dayside oval, J. Geophys. Res., 94, 5515-5522, 1989.

Potemra, T. A., R. E. Erlandson, L. J. Zanetti, R. L. Arnoldy, J. Woch, and E. Friis-Christensen, The dynamic cusp, J. Geophys. Res., 97, 2835-2844, 1992.

Sibeck, D. G., R. E. Lopez, and E. C. Roelof, Solar wind control of the magnetopause shape, location and motion, J. Geophys. Res., 96, 5489-5495, 1991.

Slavin, J. A., and R. E. Holzer, Solar wind flow about the terrestrial planets 1. Modeling bow shock position and shape, J. Geophys. Res., 86, 11401-11418, 1981.

Vorobyev, V. G., SC-associated effects in auroras, Geomagn. Aeron., 14, 72-74, 1974.

Walker, A. D. M., R. A. Greenwald, W. F. Stuart, and C. A. Green, STARE auroral radar observations of Pc5 geomagnetic pulsations, J. Geophys. Res., 84, 3373-3388, 1979.

Wilken, B., C. K., Goertz, D. N. Baker, P. R. Higbie, and T. A. Fritz, The SSC on July 29, 1977 and its propagation within the magnetosphere, J. Geophys. Res., 87, 5901-5910, 1982.

Zhou, X., and B. T. Tsurutani, Rapid intensification and propagation of the dayside aurora: Large scale interplanetary pressure pulses (fast shocks), Geophys. Res. Lett., 26, 1097-1100, 1999.