Auroral substorm response to solar wind pressure shock

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Abstract **Two cases of auroral substorms have been studied with the Polar UVI data, which were associated with solar wind pressure shock arriving at the Earth. The global aurora activities started about 1—2 min after pressure shocks arrived at dayside magnetopause, then nightside auroras intensified rapidly 3—4 min later, with auroral substorm onset. The observations in synchronous orbit indicated that the compressing effects on magnetosphere were observed in their corresponding sites about 2 min after the pressure shocks impulse magnetopause. We propose that the auroral intensification and substorm onset possibly result from hydromagnetic wave produced by the pressure shock. The fast-mode wave propagates across the magnetotail lobes with higher local Alfven velocity, magnetotail was compressed rapidly and strong lobe field and cross-tail current were built in about 1—2 min, and furthermore the substorm was triggered due to an instability in current sheet.**

Keywords: auroral substorm, solar wind pressure shock, hydromagnetic wave.

Substorm is a basic solar wind-magnetosphere-ionosphere coupling process. It has been the key problem in magnetospheric physics in the past decades. Substorms are closely related to interplanetary variations. Solar wind dynamic pressure variations, IMF *Bz* component, interplanetary shocks all can trigger substorms and produce geomagnetic effects. In different interplanetary conditions, the solar-magnetosphere coupling mechanisms may be different, which are responsible for the transfer of energy, momentum, and plasma from the solar wind to the magnetosphere and the ionosphere. Up to now, several substorm models have been proposed[1—7] to explain the internal triggering processes due to plasma instability in current sheet and external triggering processes due to IMF *Bz* northward turning for substorm onsets in southward IMF conditions. All these works were based on the fact that the magnetic field connection between IMF and magnetic field at dayside magnetopause play a main role in the solar wind-magnetosphere coupling.

Recently, the end-to-end monitoring of Sun-Earth environment by the fleet of International Solar-Terrestrial Physics (ISTP) spacecraft and complementary ground-based observations affords unprecedented opportunities to study the magnetospheric response to strong disturbances in the solar wind, and the interaction of the shocks in the solar wind, particularly those associated with interplanetary pressure shocks and coronal mass ejection. The observations show that the effects of solar wind pressure suddenly increase on the magnetosphere is remarkable. When the solar wind dynamic pressure suddenly increases, the magnetosphere is compressed, beginning at the dayside magnetopause and then continuing down the tail. If the compression occurs, the principal change in the magnetosphere will be to shrink in size and increase its magnetic field strength accompanied by rapid motion of the plasma "tied" to those field lines, and leads to the changes in magnetic field and the plasma in various regions in the magnetosphere[8]. Sibeck et al.[9] found that the sudden sharp increase in solar wind pressure initiated both the ground response and the ringing of the outer magnetospheric magnetic field. Gonzalez et al.[10] have shown that most storm sudden commencements (SSCs) are caused by interplanetary shocks associated with coronal mass ejections (CMEs). There is a close relationship between solar wind pressure shock and auroral activities. The pressure shock may cause dayside auroral activity[11,12], and also can trigger substorm. Kokubun et al.[13] proposed that the expansion phase of substorm can be triggered by the sudden solar wind dynamic pressure increase when the IMF must have been initially southward for a period of the order of 30 min or longer. A quite similar relation between the IMF direction and the effects of solar wind pressure increase on substorm activity was pointed out by Pretrinec et al.[14]. Shue et al.[15] recently presented another study in which they demonstrate how increased solar wind plasma density correlates well with substorm activity, but only as long as IMF *Bz* is negative. Jacquey[16] investigated the effect of changes in the IMF and solar wind plasma parameters on that seen by the ISEE1 satellite. He also noted that effective substorm triggering by solar wind pressure pulse only occurred during the periods of already previously enhanced lobe magnetic field. The compressing trigger of substorm can be readily understood as the onset of the reconnection caused by the increased pressure on the enhancement of reconnection at an existing reconnection site.

All the above studies emphasized the fact that the southward IMF plays an important role in the substorm onset associated with solar wind pressure shocks. In this note, we try to illustrate the possibility that the sharp increase in solar wind pressure triggered substorm onset without southward IMF with two new observations.

1 Observations

The two events presented here were recorded in a sequence of UVI images which onboard on Polar spacecraft. During these events Polar was passing through the

Northern Hemispheric polar cap sky, and the UVI was operating with a single Lyman-Birge-Hopfield Band filter (LBHlong: 160—180 nm) at 36.8 s time resolution, and recorded the whole processes of auroral substorm evolutions. Prior to the auroral activities, the Wind and Geotail located in upstream of solar wind observed the interplanetary shocks propagating to the Earth. The pressure shocks were due to solar wind ion densities and velocities increase discontinuity associated with CMEs. Prior to shock arrival, the corresponding IMF with IMF $Bz\approx0$ and southward in a short interval favor to examine the role of solar wind pressure shock playing in Solar-Terrestrial coupling processes. The observations in synchronous orbit and other regions are very helpful to studying the responses of magnetosphere and ionosphere to solar wind pressure shocks.

(i) 1998-08-26 event. The solar wind pressure shock first was observed at about 06 : 41UT by Wind which was located at $(x, y, z)_{GSM} \approx (117, -23, 3)R_E$ (see fig. 1). The data show that there are IMF, ion density, and velocity discontinuities, and produce dynamic pressure shock. At downshock (unshocked) IMF has southward component in a short period. At upshock (shocked) IMF *Bz* turned northward in about 1 min, the magnitude of magnetic field jumped from about 6 nT to 22 nT, ion density from about 6 cm^{-3} to 14 cm^{-3}; the velocity from 450 km/s to 600 km/s; and dynamic pressure from about 2 nPa to 8—10 nPa. This shock structure kept for about 50 min, then decreased slightly, but still in a higher value (7—8 nPa). The pressure shock front fluctuated slightly due to the change in density. At about 06 : 49 UT, this shock was also observed by Geotail located at $(x, y, z)_{GSE}\approx(25, 7, 0)R_E$, its structure did not change except that IMF Bz only has about 10 min southward component at down shock. The arrival times of shock at Wind, Geotail and dayside magnetopause are different. With the magnetic field data from Beijing Ming Tomb Station, we determined the SSCs time due to the shock arrival being about 06:51 UT, and inferred that the shock arrived at dayside magnetopause at 10 R_E at about 06:51 UT.

During this event, the UVI of global auroral activity was taken by Polar spacecraft which was positioned at about 8.8 R_E altitude in the polar region (shown in Plate Ⅰ(a)). At 06:50:52UT, prior to arrival of pressure shock, the remnants of previous auroral activity in the 18 : 00—24 : 00 MLT were still visible, at about 06:53 UT, postnoon aurora brightened suddenly, at the same time, nightside aurora also started intensification, but faint. Then about 1—2 min later, the nightside aurora intensified rapidly. At about 06:57 UT, the intensity approached the maximum. The auroral luminosity initiated almost at all local times in nightside, it was most intense in 18 : 00—24 : 00 MLT, and east-west asymmetrical. The dawnside auroral zone is a little narrow and located in the lower-latitude region. The intensity center was over 70°MLAT in the 18 : 00—21 : 00 MLT, and less than 70°MLAT in the 21 : 00—24 : 00 MLT. A few minutes later, the aurora extended to poleward over 80°MLAT, equatorward lower 60°MLAT, and propagated eastward. By 07 : 30 UT, the auroral activity gradually quenched, and recovered to the previous level. In contrast to the isolated substorm, this kind of auroral substorm did not appear the west-traveling surge and the initial brightening region was extensive.

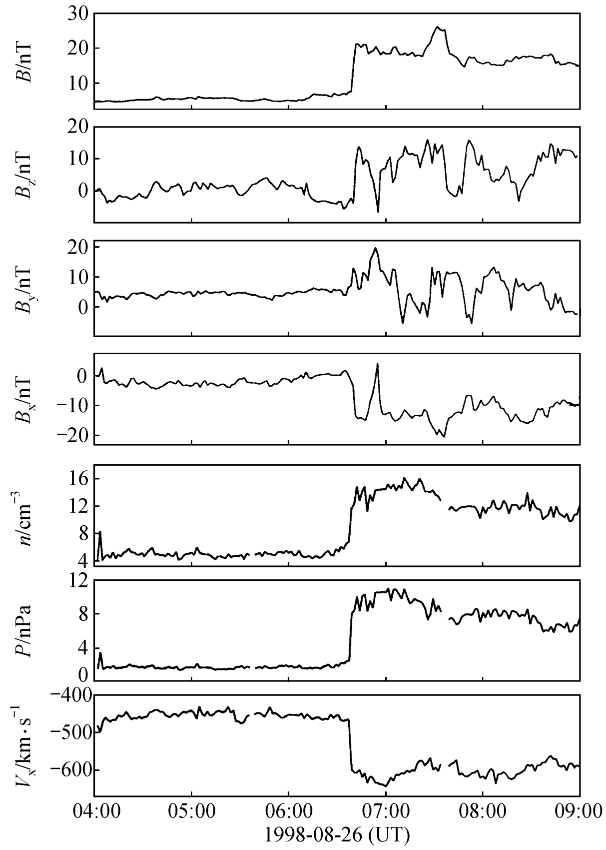

Fig. 1. The IMF and solar wind plasma data observed at Wind for 1998-08-26 event.

During this event, the geomagnetic field in the polar region response to pressure shock appeared dramatically. The *AL* index decrease began at about 06:53 UT, then decreased rapidly to – 1200 nT with a ratio of ~200 nT/min. This indicates that the *AL* index is very sensitive to the change in solar wind pressure. At the same time, the change of local electric ejection index *CU*, *CU* from CANOPUS, and the *H* component of magnetic field from SESAME, Antarctica, appear similar to that of *AL*. It is evident that the auroral electric ejection increased rapidly in polar ionosphere, and was consistent with the interval of the auroral activity.

At the synchronous orbit, LANL1, LANL4 and GOES8 were located at about (6.6R_E, 2.3MLAT,

07:30MLT), (6.6R_E, −10.2 MLAT, 13:40MLT), and $(x, y, z)_{GSM} \approx (-6, -3, 1)R_E$, respectively. All of them had observed the response of inner magnetosphere to pressure shock in their observation sites. LANL4 observed that the energy fluxes of protons and electrons were enhanced rapidly. This is consistent with the time of dayside auroral activity; then about 1 min later, LANL1 observed that the density and energy flux of high energetic protons increased, in addition, the α flux at both LANL1 and LANL4 sites increased apparently. At about 06:53 UT, GOES8 at nightside observed the magnetic field enhanced pronouncedly. This suggest that the compressing effectiveness by pressure shock propagated to that region and made the magnetic field become shock-like structure due to the wave speed being slower in inner magnetosphere than that in outer magnetosphere.

The magnetic field was measured in northern tail lobe by IMP8 which was positioned at $(x, y, z)_{GSM} \approx (-24, 0, 19)$. The characteristics of magnetic field are as follows: before 06:53 UT, the direction of magnetic field was sunward with a small southward component, this is the feature of the northern tail lobe field. It shows that IMP8 was in the lobe at that time. At about 06:55 UT, the magnetic field changed suddenly, IMF Bx changed from sunward (≈20 nT) to antisunward (≈ −20 nT), IMF By increased from zero to about 20 nT, and IMF Bz turned northward, got to about 10 nT. The changes caused by the shock arrived at the site of IMP8. The magnetic field with $Bx \approx -20$ nT, $By \approx 20$ nT, and $Bz \approx 8$ nT was just the magnetic structure in shock. The change in magnetic field indicated that the magnetosphere was compressed when the shock arrived at that region, the magnetopause boundary moved inward, and led IMP8 to get out of tail lobe, and into magnetosheath. The magnetic field observed by IMP8 suggests that the interplanetary shock got into magnetosheath and propagated along the magnetosheath to the down tail, by about 06:55 UT reached tail about 24 R_E. Assuming that the shock moved with a uniform velocity, then at about 06:53 UT, it may get near-magnetotail $x \approx -7R_E$, and acted on the near-Earth magnetotail.

(ii) 1998-09-24 event. Another event associated with pressure shock occurred on September 24, 1998. The first evidence of pressure shock arrival was a rapid increase in dynamic pressure and magnetic field with the rotating direction observed by Wind about 23:21 UT, which was located upstream of solar wind $(x, y, z)_{GSM} \approx (184, 15, -6)R_E$, then observed by Geotail at $(x, y, z)_{GSE} \approx (20, -22, -2)R_E$. Measurement of the IMF and solar wind plasma is shown in fig. 2. It it shown that IMF and plasma increased discontinuously, the IMF become stronger mainly in the y_{GSM} direction, IMF Bz increased from about zero to 7—10 nT; B jumped from 14 to 40 nT; the solar wind density increased from 8 to 20 cm^{-3}, velocity increased from 420 to 650 km/s, producing dynamic pressure from 2 to 15 nPa. The shock arrived at magnetopause at 10 R_E at about 23:44 UT[17].

Meanwhile, Polar spacecraft was at the altitude about 8.9 R_E distance around the center of polar cap, and recorded the progression of the auroral substorm (see Plate Ⅰ-7—12). At 23:42:53 UT, prior to arrival of the pressure shock, the nightside oval was more intense due to remnants of previous activity. The auroral luminosity was first observed to increase near noon at about 23:45 UT, the remnant of previous aurora brightened again in the nightside oval, and about 2 min later it increased rapidly, the aurora was more intense at 18:00—24:00 MLT. At first the intensity center was around 65°MLAT, and then drifted to higher latitudes. The poleward edge of oval moved quickly from ~70° to ~75°MLAT. The auroral luminosity reached the peak at about 23:52 UT, and then gradually decayed, by about 00:30 UT, Sept. 25, 1998, the auroral activity recovered to lower level.

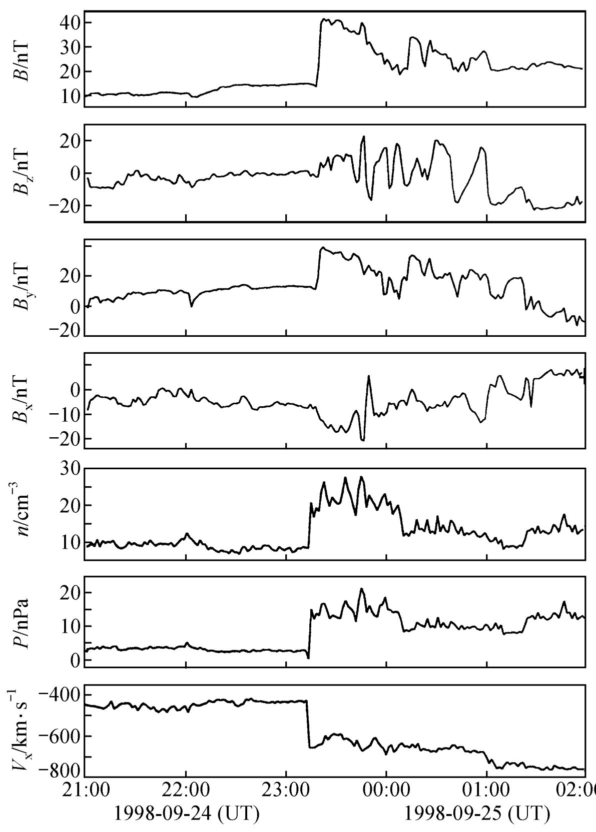

Fig. 2. IMF and solar wind plasma parameters observed at Wind for 1998-09-24 event.

At about 23:46 UT, the AL index varied prominently, decreased from −400 to −1600 nT in a few minutes. The geomagnetic field observed at Greenland magnetometer stations shows that the negative bay of H component first appeared at the southern station NAQ at about 23:46 UT, then the negative bay propagated to northern, which was observed by their northern stations.

The evidence of magnetosphere compressed was observed by LANL1 at the synchronous orbit. During the event LANL1 was at (6.6R_E, –0.7MLAT, 23MLT). The plasma data show that the density and energy fluxes of electrons and protons increased prominently and α flux increased apparently. The particle densities and energy fluxes changed with the features of discontinuity.

2 Discussion

The two events presented here were corresponding to the following interplanetary conditions: one with an IMF $Bz\approx0$ at least for about 1 h before the shock, another with about 10 min southward component. This time internal is less than that the magnetospheric convective response needed. Therefore, we can infer that these two events were controlled by pressure shock, and they have no close relation to southward IMF.

In contrast to isolated substorm, these two events have different spatial-temporal evolution features: The first important feature is that the time between the arrival of the pressure shock and the ionospheric response is very short. The auroral substorm occurred 3—4 min after pressure shock arrived at Earth's magnetopause. The response is too rapid for magnetospheric convection processes. The timescale for convection response is at least about 30 min[4], while for response to pressure shock it is only its 1/10, same as Alfven characteristic time. This suggests that the inner magnetosphere and ionosphere respond to pressure shock quite quickly. Such a quick transport of the energy possibly is related to hydromagnetic wave fast- mode. It was found that during the Earth on the interplanetary shock passage, the shock compresses the magnetosphere and propagates to down tail[18]. In the 1998-08-26 event, IMP8 observed that it took about 4 min for the shock propagating from the dayside magnetopause to tail $x \approx -24R_E$, On average, at about 06:53UT, the shock would reach $x \approx -7R_E$ in the magnetotail. The observations at the synchronous orbit also confirmed magnetospheric response with that LANL1 at dayside first observed the changes of particle energy (at about 06:53UT), when LANL4 located at dawnside observed (06:54UT) the similar phenomena. Hence, we proposed that the pressure shock, the step function like, impulse to the magnetosphere when it passed over the Earth. At dayside the magnetosphere was compressed strongly, and results in the loss cone instability, and causes the enhancement of auroral precipitation, and leads to dayside auroral activities. While in nightside magnetosphere, solar wind compression produces hydromagnetic fast-mode, the fast-mode has a higher Alfven velocity due to stronger magnetic field and smaller plasma density in magnetotail lobes. The compressive effects by pressure shock can be transported crossing the lobe sooner, and get into the plasma sheet, therefore, nightside magnetosphere would respond to the solar wind pressure shock in 1—2 min timescale. This is consistent with GOES observation, which showed that the magnetic field in night synchronous orbit changed about 06:53:30UT, just tens of seconds after the arrival of shock. Typical fast-mode speed in near-tail lobe is of the order of 6000 km/s[18], implying traversal of a 25R_E tail radius in only a few tens of seconds. Consequently, it is expected that the effect of compression of shock reached inner or plasma sheet in a few tens of seconds after it arrived at corresponding tail magnetopause. The auroral substorm in this study shows that after initial intensification in the whole auroral oval, it intensifies rapidly in about 2 min later at nightside, corresponding to *AL* decreasing dramatically, implying that a strong field-aligned current had been built. These indicated that the disturbance started in an extensive region, then a strong auroral precipitation occurred, which may be due to a burst process in near-tail around the equator. Prior to the nightside auroral activity pronouncedly intensified, the observation by GOES8 and LANL1 at the synchronous orbit also confirmed that the energy of protons and electrons near the magnetic equator both increased suddenly. This shows that the disturbance in near tail preceded the nightside strong auroral activities, and near the time of shock passed over the corresponding magnetopause. Collier et al.[18] showed with their study of theory and observations that when pressure shock impulses the magnetotail, the lobe field increased rapidly and the tail establishes a new equilibrium in about 2 min, i.e. a strong crossing-tail current might have been built in the magnetotail corresponding to the lobe field enhancement. This kind of configuration in tail is instable, therefore, the rapid intensification in nightside auroras and dramatic changes of *AL* indexes must have been caused by an instability in near-tail plasma, such as the ballooning instability studied by Pu et al.[6].

The second feature of the auroral substorm events in this study is that the auroral substorm initiated in an extensive local time, very different from that of isolated substorm. The isolated substorm described by Akasofu is as follows: aurora brightens initially in a local region near the nightside meridian plane of oval, then the region of bright expansion phase aurora expands poleward, and forms west traveling surge. This process was thought caused by the cross-tail current disruption due to plasma instability in the tail current sheet, and the disruption region extends to down tail and travels to west. However, for the two auroral substorms associated with pressure shock in this study, the most distinguishing feature is the latitudinal expansion of the auroral luminosity and enhancement of incident energy flux at all local time rather than within a limited longitudinal region as in the isolated substorm described above. This may be related to the region of interaction between the pressure shock and magnetosphere. Usually, the plasma sheet is thinner in the center than at two flanks, in particular during southward IMF. The magnetic field reconnection between IMF and dayside magnetopause field transports the magnetic field from dayside magnetosphere to magnetotail by magnetospheric convection, makes tail lobe field increase, and current sheet becomes thin. Since the occurrence rate of reconnection near the meridian is higher than that in two flanks, the magnetic field near meridian in the tail is stronger than at two flanks, and the tail current sheet is thinner in center region than in two flanks. But the interaction between pressure shock and magnetosphere is different from the interaction between IMF and magnetosphere. The pressure shock forces on the magnetosphere in all boundaries simultaneously, the plasma sheet is compressed on both center and flanks, and the current sheet might become thin in the extending longitudinal region, the energy density increases in a larger longitudinal region. This may be the reason why the auroral substorm associated with pressure shock has no very close relation to local times.

Karlsson et al.[20] found in their study of substorm quenching and multiple onsets that the substorm onset has been triggered by a solar pressure pulse after a period of southward IMF. An incomplete substorm occurred when the solar wind pressure decreased, in spite of a continuous southward IMF, due to the magnetosphere expansion. However, the substorm can develop fully when there is a continuously high solar wind pressure. For the events presented here, the shock kept high pressure for a long time, and the magnetosphere was compressed enough time to let the substorm develop completely. The substorm developed and recovered both quickly, lasting about 40 min. After that, the auroral activity quenched gradually, although the solar wind pressure still was high. This indicates that the magnetosphere needs to be refilled after energy release. This feature is not different from the substorm associated with southward IMF.

Our observations point out that the solar wind pressure shock is independent of southward IMF in triggering substorm. We propose that substorm onset associated with solar pressure shock may be explained based on hydromagnetic wave. When the pressure shock impulses the nightside magnetosphere, and launched MHD fast mode wave. The fast-mode wave propagates across the magnetotail lobes with higher local Alfven velocity, magnetotail was compressed rapidly and strong lobe field and cross-tail current were built in about 1—2 min, and furthermore the substorm were triggered due to an instability in current sheet. We believe that solar wind pressure shock plays an important role in the substorm process, which is worthy to be studied farther.

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