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GLOBAL AURORAL RESPONSE TO A SOLAR WIND PRESSURE PULSE

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ABSTRACT

A global intensification of the aurora was observed by the Ultraviolet Imager on the NASA Polar spacecraft in conjunction with the arrival of the sheath from a solar coronal mass ejection. The aurora was first observed to brighten on the dayside and then the intensification progressed rapidly toward the nightside. During this time the IMP-8 spacecraft in the solar wind recorded a 35-minute period of increased solar wind dynamic pressure. A small substorm (or, possibly pseudobreakup) occurred within a minute of the arrival of the auroral intensification on the nightside in conjunction with a second peak in the dynamic pressure. We propose that the intensification of the aurora can be explained on the basis of the compression of the magnetopause and the generation of hydromagnetic waves by the rapid increase in the solar wind dynamic pressure. It is also evident that the substorm was triggered by waves, generated by a second rise in the dynamic pressure, that propagated to flux tubes connected to the premidnight auroral region.

INTRODUCTION

One of the unsolved problems of magnetospheric physics is the extent to which several competing processes are responsible for the transfer of energy, momentum, and plasma from the solar wind to the magnetosphere and the ionosphere. The prominent processes are magnetic merging of the solar wind interplanetary magnetic field (IMF) with Earth's dipole magnetic field that transfers magnetic flux to the magnetosphere and accelerates plasma in the boundary layer (Dungey, 1961), viscous interaction at the magnetopause boundary that permits transfer of solar wind momentum and diffusive plasma entry to the magnetosphere (Axford and Hines, 1961), impulsive entry of high density solar wind plasma features that have a scale size smaller than the magnetospheric cross section (Lemaire, 1977), and transmission of hydromagnetic waves into the magnetosphere by a sudden increase in the solar wind dynamic pressure (Dessler and Parker, 1959). The viscous interaction, which has been invoked to explain intense aurorae in the afternoon region (Lundin and Evans, 1985), and the impulsive entry process, which may be responsible for dayside bright spots in the aurora (Lui and Sibeck, 1991), have not been shown to be mechanisms capable of significant transfer of energy, momentum and plasma to the magnetosphere, although they appear to be important for some intense dayside auroral activity. Alternatively, the magnetic merging (Russell and McPherron, 1973) and hydromagnetic wave (Dessler *et al.*, 1960) theories were developed to explain the occurrence of more energetic phenomenon such as geomagnetic storms and substorms. The former is widely regarded as the dominant mechanism since, during periods of southward orientation of the IMF, the theory predicts that the coupling of the IMF to Earth's dipole field enables a large transfer of energy and plasma from the solar wind, and that the efficiency of this process is sufficient to account for the magnitude of energy dissipated during auroral substorms. Although the hydrodynamic wave mechanism does not produce a transfer of energy to the magnetosphere comparable in magnitude to substorm losses, we show that the generation of these waves can have a significant role in global auroral activity and substorms.

Another important problem is the triggering of substorms by rapid changes in the solar wind dynamic pressure or IMF orientation. The main question is whether a growth phase or preconditioning of the magnetosphere is necessary for discontinuities in the solar wind magnetic field and dynamic pressure to be effective in triggering a substorm. Previous studies of storm sudden commencement (SSC) events have emphasized the role of the B_z orientation of the magnetic field. From a study of 36 SSC events Burch (1972) concluded that either a southward interplanetary magnetic field (IMF) or a large magnetic field strength was required to produce a substorm. Kokubun *et al.* (1977) surveyed 125 SSC events and also concluded that substorm triggering was dependent on the previous state of the magnetosphere. Specifically, a high probability of triggering occurred when the magnitude of preceding AE activity was large and the IMF Bz component was negative or decreasing for the preceding 30 min. Recently, Brittnacher *et al.* (1998) have shown that substorms can occur for $Bz \cong 0$ if there is a reasonably large B_x or B_y component. Three responses to a solar wind impulse are possible: (1) the magnetosphere is compressed but no substorm occurs, (2) a growth phase is initiated, or (3) a substorm is triggered. The first generally occurs if the solar wind IMF had previously been small or northward oriented for an extended period of time during which little energy storage is expected. The second occurs if the solar wind impulse is accompanied by a southward turning of the IMF, leading to increased energy storage. The third occurs when the IMF had previously been southward and considerable energy storage had taken place. In this last case, the impulse is sufficient to trigger the release of the stored energy. From this point of view a preconditioning of the magnetosphere is necessary, although the solar wind IMF and dynamic pressure conditions that are most effective for producing substorms are still not completely determined.

New observations of the global aurora at sufficient time resolution to monitor the effect of a pressure pulse on precipitation have been obtained recently by the Ultraviolet Imager (UVI) on the NASA Polar spacecraft (Torr *et al.*, 1995). Here we describe the intensification of auroral precipitation observed on October 1, 1997 that was associated with a pressure pulse lasting more than 35 min, as recorded by the IMP-8 spacecraft in the solar wind. The large enhancement of the solar wind dynamic pressure signaled the arrival of the preceding plasma sheath from a coronal mass ejection (CME) from the sun. The auroral precipitation was first observed to intensify on the dayside and then proceeded toward midnight. A substorm was observed following the arrival on the nightside of the auroral intensification due to a second rise in the dynamic pressure. We propose that the intensification of the aurora and the triggering of the substorm result from the generation of hydromagnetic waves by the sudden pressure enhancement of the solar wind. The onset of the substorm did not coincide with the initial arrival of the pressure pulse, but rather with a second small increase in the dynamic pressure. There is evidence that an instability was triggered when the hydromagnetic waves reached the flux tubes connected to the premidnight region.

OBSERVATIONS

The first evidence in the solar wind of the arrival of the CME sheath on October 1, 1997 was a rapid increase in the dynamic pressure observed at the IMP-8 spacecraft located at $(x,y,z)_{GSM} = (10,32,5)$. Measurements of the solar wind IMF and plasma are shown in Figure 1. The arrival times of the solar wind structures at IMP-8 and at the magnetopause are expected to differ by at most a few minutes. The beginning of a pressure pulse that continued for about 35 min is seen by the rapid rise in the dynamic pressure at 0058 UT from a relatively steady 4 nPa to as high as 15 nPa, within a few minutes. The dynamic pressure remained between 13 and 15 nPa until 0133 UT. Two peaks in the dynamic pressure occurred at about 0102 and 0110 UT, mostly due to an increase in the ion density. The pressure returned to approximately its original value at 0140 UT, followed by small fluctuations about this value. The increase in the dynamic pressure was due to an increase of about 10% in the solar wind speed and a doubling of the solar wind density. The 15-s average IMF measurements, plotted in GSM coordinates in Figure 1, show that the magnetic field was relatively weak for an hour prior to the pressure pulse. During the pressure pulse the IMF was predominantly oriented in the dusk-to-dawn (negative B_y) direction with a maximum magnitude of 10 nT. The B_z component had a zero average value with ±2 to 3 nT fluctuations. Hence, during the pressure pulse the condition $|B_y| >> |B_z|$ mainly prevailed. A rotation in the IMF orientation and a decrease in the total magnetic field occurred during the second peak in dynamic pressure between 0108 and 0114 UT. We will later see the relationship between this feature and the onset of a small substorm. A larger increase in the magnetic field was observed at the end of the pressure pulse where a large positive B_y and B_z occurred.

The global ionospheric response to the pressure pulse was recorded in a sequence of UVI images. A selection of UVI images is shown in Figure 2. During this event the UVI was operating with a single Lyman-Birge-Hopfield

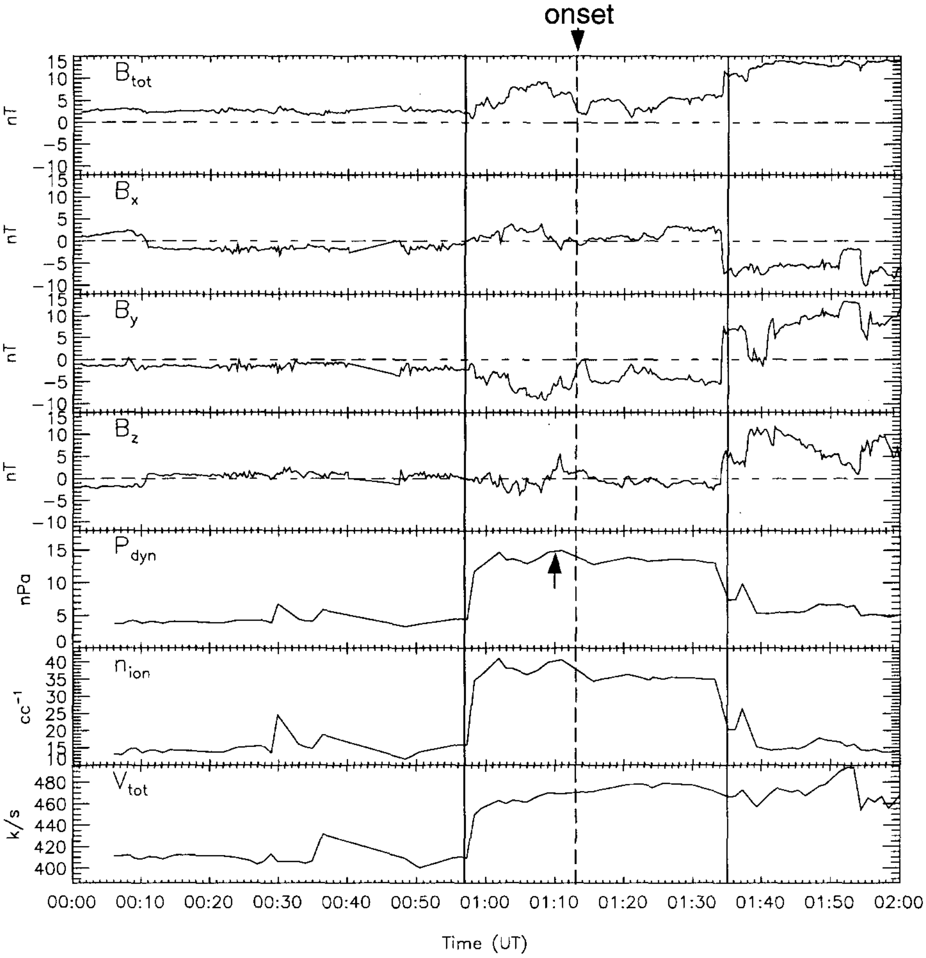

Fig. 1. Solar wind magnetic field and plasma moments observed at IMP-8. The solid lines mark the approximate beginning and end of the pressure pulse. The arrow indicates the second rise in the dynamic pressure that results in auroral intensifications that progress toward the nightside and a substorm. The dashed line marks the onset of the small substorm at 0113 UT.

Band filter (LBHlong: 160–180 nm) at 36.8 second time resolution. The auroral luminosity measured by this filter is proportional to the energy flux of precipitating electrons. The dayside airglow was removed by empirical modeling of the airglow intensity from a sequence of images on this day. The images are calibrated in energy flux (ergs cm^{-2} s^{-1}) of precipitating electrons based on auroral transport modeling (Germany *et al.,* 1997). Contamination from spacecraft "wobble" smears the image by approximately 5 degrees MLat in the dawn-dusk direction.

At 0056:58 UT, prior to the arrival of the pressure pulse, the dawnside oval was more intense than the duskside, and remnants of previous high-latitude activity near midnight were still visible. The auroral luminosity was first observed to increase near noon at 0058:48 UT, and its maximum intensity in this region was achieved about 2 min later at 0100:38 UT. The intensification progressed rapidly along the dawnside within the first few minutes while a longer delay in the initial intensification was noted on the duskside. The auroral luminosity in the 22 to 0 MLT region gradually increased beginning at 0102:29 UT and peaks at 0109:50 UT. Thus, the intensity ramps up for about 7 min, which is about 3 times longer than the initial ramp seen near noon. At 0113:31 UT, about 15 min after the arrival of the initial pressure pulse, a rapid intensification of the aurora near midnight occurred that moved

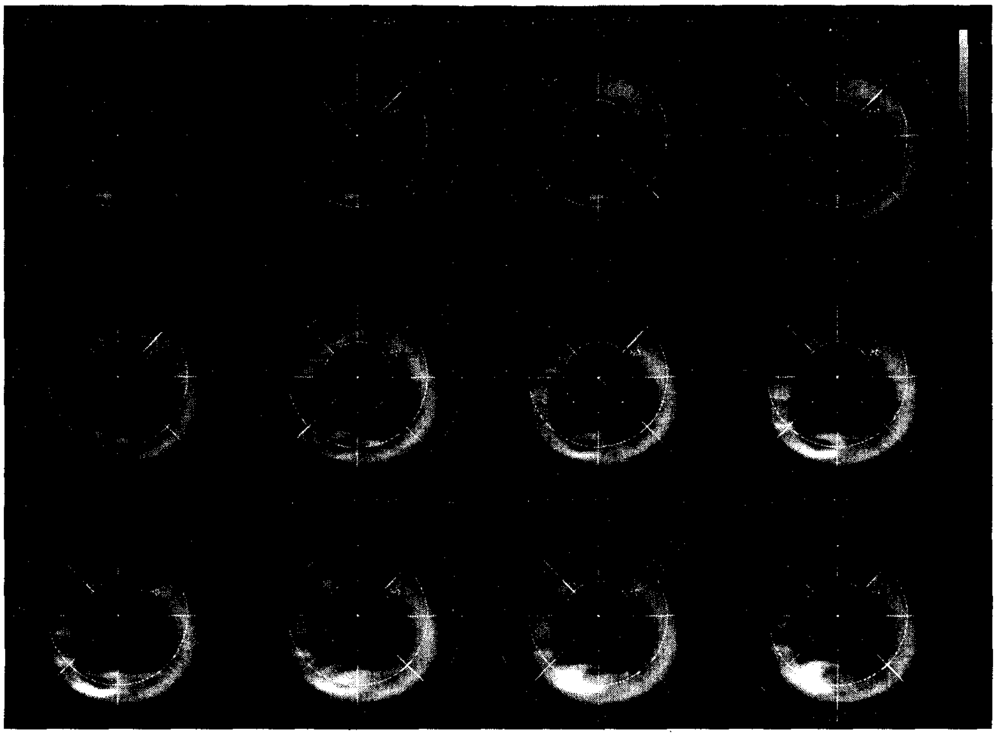

Fig. 2. Selected UVI images illustrating the progression of the precipitation enhancement from the dayside toward the nightside and the substorm. The images are plotted in Apex (Richmond, 1995) magnetic latitude (MLat) and magnetic local time (MLT). The times shown are the beginning of each 36.8 s integration period. The sharp edge across the top of the images from noon to 6 MLT is the edge of the UVI field of view.

rapidly poleward, as seen in the next two images. This intensification has some characteristics of a substorm, but does not completely fit the classical substorm pattern since it was not isolated. This substorm (or, possibly pseudobreakup) occurs in the midst of pre-existing high-latitude activity in the nightside oval. A poleward progression of the intensification, but not motion of the high-latitude boundary, of the aurora can be seen in the last three images in the sequence. The substorm occurs within a few minutes of the arrival of the auroral intensification produced by the second peak in the dynamic pressure. The increased luminosity due to the second peak in the pressure pulse is too faint be seen in these images, but is apparent when plotted in a different format below.

Variations in intensity and magnetic latitude of the day and night side auroral oval can be more clearly seen by constructing a "keogram" from UVI images. The electron energy flux derived from the auroral luminosity is plotted in magnetic latitude and time (UT) for the 12 and 22.5 MLT regions in Figure 3. Since the spacecraft wobble smears the image in magnetic longitude near noon and midnight over a region smaller than one hour MLT, it does not affect the resolution of this keogram. At the time of arrival of the pressure pulse the auroral luminosity first increases and achieves its greatest intensity between 75 and 80 degrees MLat. Within the next 2 min the equatorward boundary moved down to 72 degrees MLat. The equatorward boundary recovered to 75 degrees MLat after about 6 min. The second peak in the pressure pulse caused an intensification and an equatorward shift of the low-latitude boundary of the aurora beginning at 0110 UT. Thus, the auroral response to the second peak was similar to the initial rise in dynamic pressure, but weaker. In the 22 to 23 MLT region (bottom plot in Figure 3) the first intensification is seen at 0103 UT between 66 and 68 degrees MLat. The rapid poleward expansion of the luminosity at 0114 UT is evidence of the onset of a substorm. Due to the pre-existence of activity at higher latitude in the oval the poleward boundary shows little change. The auroral luminosity weakens on the dayside a few

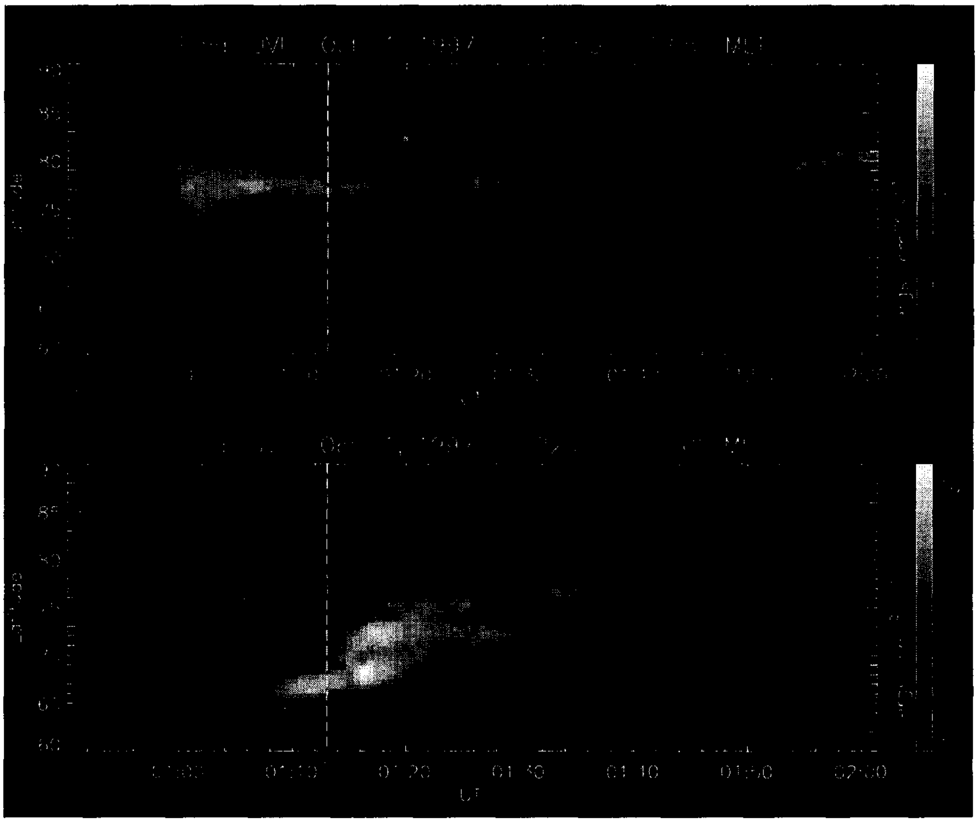

Fig. 3. Keograms constructed from UVI images showing a time series of precipitation energy flux for the 12 and 22.5 MLT regions. Each vertical strip corresponds to a 36.8 s image averaged over 0.5 degree MLat and 1 hour MLT increments. The vertical dashed line indicates the onset of the substorm.

minutes after the dynamic pressure drops at 0135 UT. On the nightside the auroral luminosity drops off sharply about 20 min after the solar wind decrease in pressure.

An interesting feature of this event is the timing of the ionospheric response from a global point of view. To illustrate the time sequence of the auroral response a stackplot of auroral power for each hour of MLT was constructed as shown in Figure 4. The power deposited in each hour MLT at auroral latitudes (60 to 85 degrees MLat) by electron precipitation is plotted versus time. Each trace is shifted vertically to clearly distinguish them. The initial intensification of the aurora is simultaneous in the region between 10 and 15 MLT, within the time resolution of the UVI. The progression of the auroral intensification along the dawn flank of the oval between noon and 3 MLT occurs rapidly, within about one minute. The progression of the intensification on the duskside takes as long as 5 min to reach 21 MLT. Thus, there is an asymmetry between the dawn and dusksides in the timing of the first arrival of the effect of the pulse. The effect of the pressure pulse at all local times is seen as an upward ramp in the energy flux that peaks earliest near noon. The slope of the ramp in precipitation energy is steeper on the duskside and peaks at a larger value than the dawnside.

A second increase in the dynamic pressure arriving at the magnetopause at 0106 UT and peaking at 0110 UT (indicated by the arrow in Figure 1) generates an increase in precipitation that progresses from the dayside to the nightside between 0108 and 0113 UT. A substorm expansion, seen as a rapid increase auroral power beginning at 0113 UT in the 22 and 23 MLT line plots in Figure 4, occurs concurrently with the arrival of the second intensification of the precipitation in the pre-midnight region. The initial rise in precipitation energy due to the

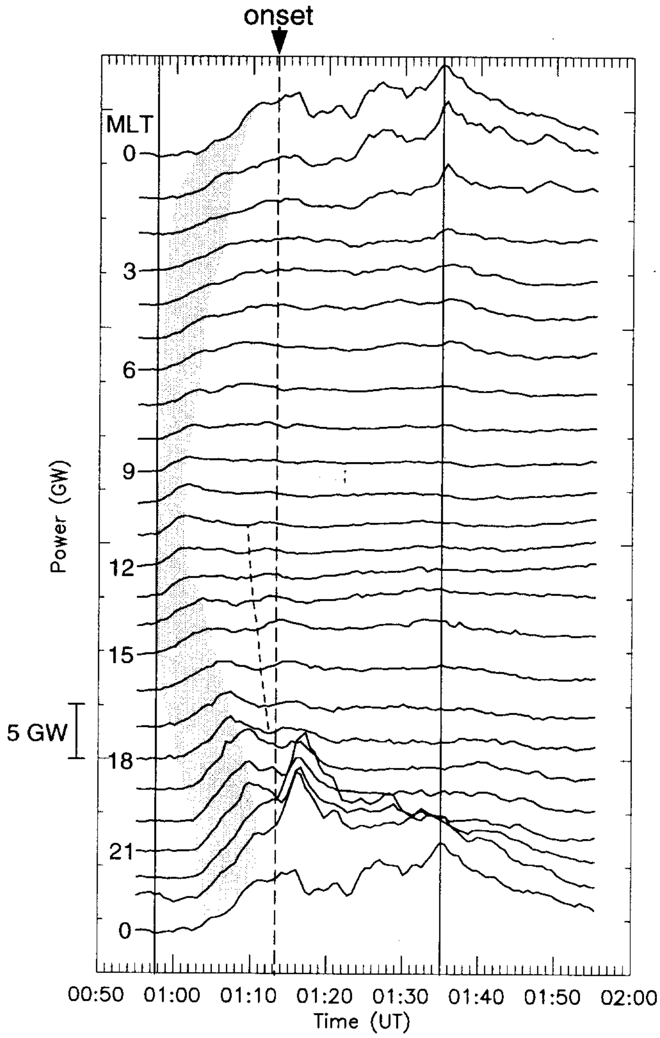

Fig. 4. Stackplot of auroral power for one hour MLT segments of the aurora. The solid lines mark the approximate beginning and end of the pressure pulse. The dashed line marks the onset of the substorm at 0113 UT. The gray area highlights the initial ranping up of auroral power following the arrival of the pressure pulse. The short-dashed line between the 11 and 18 MLT line plots shows the leading edge of the auroral intensification due to the second peak in the dynamic pressure as it propagates along the duskside toward the premidnight region.

pressure pulse in the 22 and 23 MLT region was 0.9 GW per minute. During the substorm the rise in energy was about 2.1 GW per minute, a rate that was more than twice as fast as what the pressure pulse produced.

DISCUSSION

An important feature of this event is the timing of the arrival of the pressure pulse and the development of the ionospheric response. The intensification of the dayside aurora within a minute of the arrival of the pressure pulse at Earth's magnetopause and the subsequent rapid buildup of auroral precipitation globally suggests that hydrodynamic waves are responsible for the increase in precipitation. The response is too rapid for convection processes. We propose that, during the 5 min required for the pressure pulse to traverse the magnetosphere from the front of the magnetopause to about 10 R_E downstream of Earth, the amplitude of the magnetic perturbation on flux tubes connected to the auroral zone is built up by a series of magnetosonic waves generated by the passing disturbance. On the flux tubes connected to the auroral region the transverse Alfven mode accelerates and scatters particles into the loss cone leading to enhanced precipitation. The arrival of the waves will be delayed for local times farther from noon due to the longer propagation path length. This can explain the 5-minute time difference between the initial response near noon and the first significant increase in precipitation near midnight. It does not however explain the dawn-dusk asymmetry in the response, which has also been reported for a previous magnetic cloud event (Spann *et al.* 1998). If the pressure discontinuity at the leading edge of the pressure pulse can be modeled as a planar surface oriented such that it strikes the magnetopause on the dawnside, then it seems reasonable that an asymmetry in the precipitation could be explained. The discontinuity would travel more rapidly along the dawnside of the magnetopause than the duskside with a time difference consistent with the delay between the two. However, a least squares determination of the "shock" normal based on the components of the magnetic field indicates that the assumed planar surface should strike the duskside first. Although the errors in this calculation are large due to fluctuations in the magnetic field components, a reversal of the orientation to favor the dawnside is not likely. Another possibility is that the source of the electrons that precipitate in the dusk region of the auroral oval is farther back in the tail than on the dawnside. This would be easy to verify since all pressure pulse events should exhibit the same asymmetry regardless of the shock normal orientation. The broadening of the aurora to a lower latitude of 71 degrees MLat following the arrival of the initial pressure pulse, and the second peak a few minutes later, may be explained by the increase in the dayside region 1 field-aligned current due to a compressed magnetopause. Winglee and Menietti (1998) showed using fluid simulation that the dayside region 1 currents will both increase in intensity and broaden to lower latitude immediately following the compression of the magnetopause by a solar wind pressure enhancement.

The monotonic increase in precipitation at each magnetic local time is due to the spread in the arrival time of refracted magnetosonic waves. The duration of the initial upward ramp in precipitation increases from about 2 min near noon to about 7 min near midnight. These rise times are consistent with those obtained by Dessler *et al.* (1960) based on summing ray paths for waves generated by the impact of a plane wave shock front with the magnetopause. Since the shock has passed Earth after about 3 min the perturbation to the flux tubes connected to the dayside ionosphere will decline after this time. However, the shock perturbation will continue to pass through the region magnetically connected to the nightside for more than 10 min, and thus it would be expected to influence this region for a longer period of time. The larger size of this nightside region of the magnetosphere can also account for the precipitation increasing to a greater value than on the dayside.

The fact that the large increase in the dynamic pressure did not immediately trigger a substorm is consistent with the view that a preconditioning of the magnetosphere is necessary for substorm onset. In this event, the magnitude of the solar wind IMF was small and the B_z component was approximately zero for 50 min prior to the pressure pulse. However, prior to the pressure pulse the dynamic pressure was relatively high, 4 to 5 nPa, and during the pressure pulse the IMF B_z had a (small) negative average value and $|B_y| >> |B_z|$, conditions that could provide dayside magnetic merging and a substorm growth phase. The enhanced pressure prior to 0057 UT was not sufficient, however, for a growth phase. .Otherwise it is expected that the large pressure pulse would have triggered the substorm sooner than 16 min. The second increase in the dynamic pressure arrived at the magnetopause at 0106 UT, about 7 min prior to the onset of the substorm, and peaked at 0110 UT. It was shown in Figure 4 that this second peak produced another auroral intensification that traveled away from noon toward the night side of the oval, and was most clearly seen on the dusk flank. The disturbance arrived in the premidnight region about 4 min later, coincident with the onset of the substorm. The coincidence of the arrival time of the auroral precipitation due to the second peak of the dynamic pressure and the onset of the substorm is evidence that the pressure pulse triggered the substorm. Since the increase in precipitation associated with the substorm was more than twice as rapid as the ramp up seen earlier due to the shock, and was restricted to a few hours MLT, it was probably produced by a mechanism different from Alfven waves. The rapid increase in precipitation is more characteristic of an explosive instability. Its small local time extent argues for a disruption of the cross-tail current system that was restricted to a small region in the dawn-dusk direction of the magnetotail.

Another interpretation of this event is that the northward turning of the IMF at 0109 UT, about 4 min prior to onset, rather than the small increase in dynamic pressure triggered the substorm. The intensity wave in the aurora that propagated toward the nightside may have been produced by the increase in dynamic pressure or the rotation of the IMF clock angle, or both together. The arrival of the waves generating the auroral intensification on the nightside may be coincidental with the substorm onset, not necessarily the cause of it. Rather the reduction of the solar wind electric field (associated with the northward turning of the IMF) propagated into the magnetosphere and triggered the expansion phase onset, as described by Lyons (1995). There is also a significant reduction of the total magnetic field a few minutes prior to the substorm onset that can also contribute to substorm triggering by reduction of the dayside reconnection rate. If this explanation is correct the coincidental arrival of the auroral intensity wave on the nightside with the substorm onset indicates that the reduction of the large scale electric field of the solar wind propagated into the near-midnight region at the same rate as the waves which intensified the nightside aurora. What is puzzling about this interpretation is that the same solar wind conditions prior to the substorm onset occur at the end of the pressure pulse, but no substorm or auroral enhancement was observed. Specifically, between 0115 and 0134 UT the same condition, $|B_y| >> |B_z|$, that provided the previous substorm growth phase was observed along with a significantly increased dynamic pressure, 13 to 14 nPa. These conditions should have provided a sufficient growth phase such that the rapid northward turning of the IMF at 0134 UT would have triggered another substorm. It is also probably more the case that the sharp drop in solar wind dynamic pressure at 0134 UT would be destabilizing. No increase in the auroral intensity was observed at that time; rather a decrease can be seen in Figure 1.

We consider solar wind pressure pulse events to be important in the study of substorm triggering. From our analysis of these events we find that rapid changes in the solar wind dynamic pressure may be more important for triggering of substorms than is currently thought. The ability to directly observe the propagation of the solar wind disturbance into the magnetosphere and to compare the timing of this disturbance in relation to substorm onset may provide a way to distinguish the particular mechanism of substorm triggering. For example, the enhancement of particle precipitation by waves, or lowering of mirror points by compression of the flux tubes, increases the local ionospheric conductivity and, consequently, the field-aligned current. Alfven waves launched by rapid changes in the current would propagate into the near-Earth plasma sheet region. In this region substorm onset is thought to occur as a consequence of destabilization of the cross-tail current sheet. An interplay between the stability of the tail current sheet and changes in ionospheric conductivity mediated by Alfven waves may be an integral part of the overall picture of substorm onset.

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