ENERGETIC PARTICLE INJECTIONS IN THE INNER MAGNETOSPHERE AS A RESPONSE TO AN INTERPLANETARY SHOCK

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Abstract. The response of the magnetosphere to interplanetary shocks or pressure pulses can result in sudden injections of energetic particles into the inner magnetosphere. On August 26, 1998, an interplanetary shock caused two injections of energetic particles in close succession: one directly from the dayside and the other indirectly from the nightside associated with a sudden magnetic field enhancement induced by the shock's effect on the magnetotail. The latter injection was different from a typical substorm injection in that the nightside magnetic field at geosynchronous orbit enhanced almost simultaneously over a wide range of local times within ten minutes after the arrival of the shock. Available observations and our simulations show that like the dayside, the nightside magnetosphere can also inject energetic particles into the inner magnetosphere from a wide local time region in response to a shock impact. The nightside particle injection was due to changes in magnetic and electric fields over a large region of space and thus shows that the magnetic and electric fields in the magnetotail can respond globally to the shock impact.

Keywords: interplanetary shock, substorm, energetic particle injection, drift echoes, geostationary orbit, inner magnetosphere.

Introduction

The response of the Earth's magnetosphere to solar wind pressure enhancements has been found to be quite complicated (Kaufmann and Konradi, 1969; Kokubun, 1983; Li et al., 1993; Le et al., 1993; Russell et al., 1994a; Russell et al., 1994b; Russell and Ginskey, 1995; Araki et al., 1997). It has long been known that solar wind pressure enhancements cause sudden impulses (SI's) and can trigger substorms if the magnetosphere is correctly preconditioned (Kokubun et al., 1977). Lately it has become clear that at least some solar wind pressure enhancements induce a second enhancement of the whole nightside (near-magnetotail) magnetic field that is quite different from the more localized effects of a typical substorm (Zesta et al., 2000). The shock impact of August 26, 1998 is an example of this class of events. The shock caused widespread auroral precipitation and intensive energetic particle injections into the inner magnetosphere first from the dayside and then from the nightside. We investigate the possible magnetic and electric field changes at the magnetic equator that would be required to produce the observed energetic particle flux changes associated with this shock impact by means of test-particle simulations.

Acceleration of energetic particles accompanies magnetic and electric field changes. One manifestation of such acceleration is the injection of energetic particles into the inner magnetosphere (e.g., Bogott and Mozer, 1973; Arnoldy et al., 1982) which can sometimes be observed again as one or more subsequent 'drift echoes' (Lanzerotti et al., 1967). The changes in the particle flux depend on changes in magnetic and electric fields over a large region of space. Since the motion of charged particles in magnetic and electric fields is known, studies of such particles can provide information about changes in fields. Test particle simulations are a useful tool for such studies. Such studies have been conducted to understand the magnetic and electric field changes associated with an interplanetary shock impact (Li et al., 1993; Hudson et al., 1995) and with an isolated substorm onset (Li et al., 1998; Li et al., 1999; Li et al., 2000; Sarris et al., 2002). In both cases, the time-dependent electric field was modeled as a pulse propagating radially inward. The first case represented

the most energetic particle injection ever seen. It was created by a strong and fast interplanetary shock that impacted the Earth's magnetosphere at 3:42 UT on March 24, 1991 (Vampola and Korth, 1992; Blake et al., 1992). The pulse field associated with the shock propagated through the magnetosphere (either as a magnetosonic wave or a shock wave) injected ions and electrons to as close to the Earth as two Earth radii, R_E, with energies larger than 15 MeV, creating new radiation belts, which lasted for years. In modeling an isolated substorm injection we used a similar model except that we made the pulse slower, weaker, and confined in local time, representing a localized dipolarization process, and had it originate in the magnetotail rather than in interplanetary space. This study showed that the source of injected energetic particles at substorm onset at geosynchronous orbit is from several R_E tailward of geosynchronous orbit (Li et al., 1998; Sarris et al., 2002).

In addition to the analytic field models described above, a variety of physically and empirically based models have been used to simulate the global evolution of electric and magnetic fields associated with shock impact and substorm onset. Physical models are often based on either a single-fluid magnetohydrodynamic (MHD) approximation of the magnetosphere [e.g., Lyon et al., 1998; Wiltberger et al., 2000.], or multi-fluid or hybrid formulation [e.g., Hesse et al., 1996]. In these models, the substorm occurs as a result of changes in the boundary conditions imposed on the simulation domain (Schindler and Birn, 1993). In simulations of idealized substorms, these conditions may be artificially imposed at some specific time (Birn et al., 1998; Birn et al., 1997). In event studies using global MHD codes, extensive preconditioning of the simulation domain, coupled with boundary conditions driven by the solar wind changes, are required for accurate reproduction of magnetospheric substorms (Lyon et al., 1998; Wiltberger et al., 2000; Pulkkinen and Wiltberger, 2000). Despite the increasing prevalence of global MHD models in magnetospheric research, extensive computational requirements, code complexity, and lack of general availability within the research community have heretofore limited their use as general research tools.

Here we use analytic fields to model the electric and magnetic fields associated with substorm dipolarization (Li et al., 1993; Li et al., 1998). We show the magnetosphere responded to the interplanetary shock on August 26, 1998 by injecting particles twice in close succession: first from the day side due to a direct impact

from the shock, and then from the nightside due to a field enhancement induced by the shock.

Observations and Discussions

Solar wind conditions and magnetic field measurements at geosynchronous orbit

Figure 1

Figure 1 shows selected solar wind parameters on Aug. 26, 1998 measured by the WIND spacecraft, 120 R_E upstream from the Earth and similar parameters from the Geotail spacecraft, 25 R_E upstream, and magnetic fields from the GOES-8 spacecraft, which was near local midnight in geosynchronous orbit. Panels (a)-(c) show the solar wind velocity, density, and dynamic pressure (ρV^2) (Ogilvie et al., 1995), panel (d) shows the z-component (in GSE coordinates) and the magnitude of the interplanetary magnetic field (Lepping et al., 1995) from WIND. Panels (e)-(f) show the three components (in GSE coordinate) and magnitude of the interplanetary magnetic field (Kokubun et al., 1994), panels (g)-(i) show the solar wind velocity, density, and dynamic pressure (ρV^2) (Frank et al., 1994) from Geotail. Panels (j)-(l) show the three components of the magnetic field (H_p: parallel to the Earth's rotation axis, H_e: earthward, H_n: eastward) from GOES-8.

At 4:50 UT (marked by a vertical dash dot line Figure 1), GOES-8 measured a typical substorm dipolarization of the nightside magnetic field, indicated by a decrease of H_e and an increase of H_p. In contrast, at 6:51 UT, marked by a vertical dotted line in Figure 1, GOES-8 registered a sudden enhancement of the magnetic field after an interplanetary shock, characterized by a sudden increase in the solar wind dynamic pressure, which was measured by WIND 15-min earlier and by Geotail 2-min earlier. Eight minutes later there was a second enhancement of the GOES-8 magnetic field. At the first compression, at 06:51 UT, the magnetic field at GOES-8 stretched into a more tail-like configuration. The compression that followed eight minutes later produced a further stretching of the field that was quickly followed by a dipolarization at 7:00 UT, when H_p increased suddenly while H_e decreased.

GOES-10, which was about 60 degrees west of GOES-8, observed similar magnetic changes during the same period (not shown here). At this time, GOES-9 was located midway between GOES-8 and 10. Although GOES-9 had ceased operational status and was slowly precessing instead of being 3-axis stabilized, the

total field measured at GOES-9 had a profile similar to that of GOES-8 and GOES-10. Thus, similar field changes occurred over at least the 4-hour longitudinal span of GOES-8, 9, and 10. The magnitudes of the first compression, at 6:51 UT, of the field at GOES-8, 9, and 10 were about 40 nT, 32 nT, and 30 nT respectively.

Energetic particle measurements at geosynchronous orbit

Figure 2

The energetic particle variations at geosynchronous altitude are shown in Figure 2. The top diagram of Figure 2 shows the satellite position at 6:51 UT. The omni-directional differential fluxes of electrons and protons from Los Alamos National Laboratory (LANL) sensors, which are identically designed (Belian et al., 1992), on three geosynchronous satellites, are plotted in the left and right columns, respectively, with different energy ranges as labeled.

There was an injection shortly after 4:50 UT, marked by a vertical dash-dot line. A drift-time calculation shows that it was an injection from the nightside. It was a typical isolated substorm injection measured at geosynchronous orbit, which was associated with the magnetic field dipolarization as being measured by GOES-8 during the same time (Figure 1).

At 6:51 UT when the shock impacted the magnetosphere, marked by the vertical dotted line in Figure 1, an enhancement in both electrons and protons occurred almost simultaneously at satellites located at different local times. Furthermore, the higher-energy channels also showed large variations. Higher energy electron fluxes dropped while higher-energy proton fluxes rose. Based on our previous simulations (Li et al., 1993; Li et al., 1998), we understand the decrease of the higher-energy electrons are due to the weaker source population at larger radial distances, while the increase of the higher-energy protons indicates an adequate source population at larger radial distances. Indeed, there was a solar energetic particle event prior to this time and energetic ions pervaded interplanetary space (Bale et al., 1999) and penetrated into the magnetosphere as is evident from the higher-energy proton measurements in Figure 2, which shows a gradual increase prior to the arrival of the shock.

Hereafter we focus on analyzing this shock impact event. We first tried to reproduce the observed particle features by test-particle simulations using a field model of the field configuration change caused directly by

the shock impact. Such a model was only able to reproduce the initial enhancement, at 6:51 UT, and did not give good results overall. Further analysis showed that there were, in fact, two injections in close succession associated with the shock: one from the dayside due to a direct impact from the shock, at 6:51 UT, and the other from the nightside associated with a sudden magnetic field enhancement over a wide local time region which was induced by the shock. The second enhancement, wider and higher on the flux vs time plot, of electrons was detected at satellite 1 first, then at satellite 2 and satellite 3 with a time delay equal to the drift time. The second enhancement of protons was detected at satellite 3 first, then at satellite 2 and satellite 1 with a time delay equal to the drift time.

Modeling Results and Discussions

To show that two such injections can qualitatively reproduce the data we used a field model similar to the one in Li et al. [1993], which was developed to model the sudden compression of the magnetosphere at the equator by a strong interplanetary shock. The time-varying fields, however, in the present case were associated with a much weaker interplanetary shock. The interplanetary shock compressed the geomagnetic field and is modeled as a time-dependent Gaussian pulse with a purely azimuthal electric field component that propagates radially inward at a constant velocity, decreases away from the impact point, and is partially reflected near the surface of the Earth. The modeled shock encounters the magnetosphere first at longitude ϕ_0 and subsequently at other longitudes. Explicitly, in the usual spherical coordinates (r, θ, ϕ), where r is measured from the center of the Earth, $\phi = 0^\circ$ at noon local time, positive eastward, $\theta = 0^\circ$ at the north pole, the electric field is given by

$$\mathbf{E}_w = -\hat{e}_\phi E_0 \left(1 + c_1 \cos(\phi - \phi_0)\right)^k \left[\exp(-\xi^2) - c_2 \exp(-\eta^2)\right], \tag{1}$$

where the terms in the square brackets are associated with the compression and relaxation of the magnetosphere. In Eq. (1) $\xi = [r + v_0(t - t_{ph})]/d$, $\eta = [r - v_0(t - t_{ph} + t_d)]/d$, v_0 is the pulse propagation speed, and d is the width of the pulse; $c_1 (> 0)$ and k describes the local time dependence of the electric field amplitude, which is largest at ϕ_0; $t_{ph} = t_i + (c_3 R_E / v_0)[1 - \cos(\phi - \phi_0)]$ represents the delay of the pulse from ϕ_0 to

other local times; c_3 determines the magnitude of the delay; c_2 determines the partial reflection of the pulse; $t_d = 2.06R_E/v_0$ indicates that the reflection occurs at $r = 1.03R_E$; and t_i determines the location of the pulse at the start of the simulation. Here we present results with E_0= 6 mV/m, $c_1 = 0.3, c_2 = 0.6, c_3 = 3$, $k = 1$, v_0= 1200 km/s, t_i=1400 s, $\phi_0 = 0°$ and d=80000 km. The perturbed magnetic field $\mathbf{B}_w$ is obtained from Faraday's law, and satisfies $\bigtriangledown \cdot (\mathbf{B}_E + \mathbf{B}_w)$=0 and $\mathbf{E}_w \cdot (\mathbf{B}_E + \mathbf{B}_w)$=0, where $\mathbf{B}_E$ is the background dipole magnetic field. The model thus describes the propagation of a magnetosonic pulse through the magnetosphere ignoring the variable pulse velocity due to changes in density, temperature and magnetic field.

To model the injection from the nightside, we used the same model field as shown in Eq. (1) except that we made the electric field pulse slower, weaker, relatively narrower in local time (but much wider compared to the model used for an isolated substorm injection (Li et al., 1998)), and had it originate in the magnetotail rather than in interplanetary space. The parameters for the second pulse are: E_0=0.8 mV/m, $c_1 = 1, c_2 = 0.4, c_3 = 1$, $k = 1$, v_0=150 km/s, t_i=2300 s, $\phi_0 = 180°$ and d= 35000km, $t_d = 7R_E/v_0$. For comparison, we list the model parameters used in this paper and two previous papers (Li et al., 1993; Li et al., 1998) in Table 1.

Table 1

Figure 3

Figure 3 shows the electric and magnetic field given by the model at $L = 6.6$ at noon, dawn/dusk, and midnight at the equator. At larger L values the pulses are broader and somewhat larger since the incoming and reflected pulses are further separated and there is less destructive interference between them. We superposed this time-varying field on the background magnetic field, which is modeled as a dipole field, and followed the particles using a relativistic guiding center approximation with $v_{\|} = 0, E_r = E_\theta = 0$ (Northrop, 1963)

$$\dot{W} = q\dot{\mathbf{R}}_\perp \cdot \mathbf{E}_w + \frac{M_r}{\gamma}\frac{\partial B}{\partial t}, \tag{2}$$

$$\dot{\mathbf{R}}_\perp = \frac{\hat{e}_1}{B} \times (-c\mathbf{E}_w + \frac{M_r c}{\gamma e} \bigtriangledown B), \tag{3}$$

where $\dot{\mathbf{R}}_\perp$ describes the guiding center motion perpendicular to the instantaneous magnetic field $\mathbf{B} = \mathbf{B}_E + \mathbf{B}_w$, $\hat{e}_1 = \mathbf{B}/B$ is a unit vector along $\mathbf{B}$, $\gamma = (W + m_0c^2)/m_0c^2$ is the relativistic energy factor, W is the particle's kinetic energy, $M_r = p_\perp^2/2m_0B$ is the relativistic adiabatic invariant and $p_\perp$ is the particle's perpendicular momentum.

In the simulation we followed 90,720 electrons and 94,500 protons as they drifted in the combined fields of

the Earth's dipole and the modeled pulse field, recording their energy, arrival time, radial distance, and initial conditions as they passed various local times. We modeled the particles, all of which have 90° equatorial pitch angle, before the event by distributing the test-particles in the equatorial plane at distances from L=6 to L=12.6 in increments of 0.15 R_E, in azimuth every 5°, and at energies between 33 keV and 1.44 MeV in increments of 15% for electrons and from L=6 to L=12.6 in increments of 0.15 R_E, in azimuth every 6°, and at energies between 33 keV and 3.82 MeV in increments of 15% for protons, respectively.

In the post-processing stage each particle was given a weight which depended on the assumed initial distribution in energy (power law), W_0, and in L-shell, L_0.

$$Q_{wt} = fr(L_0) \cdot W_0^{-N} \cdot L_0^2 \cdot \frac{v}{v_d}, \tag{4}$$

where N has been taken N=2.5 for protons and 1.6 for electrons based on the omni-directional LANL measurements prior to the arrival of the shock and assumed to be the same at other radial distances (this together with the geometric progression of energies, 15% increase, gives an effective power law index of 3.5 and 2.6 for protons and electrons, respectively). One L_0 in the factor L_0^2 implies that a particle initially at larger L-shell represents a larger phase space since the particles are distributed uniformly in azimuth and another L_0 is included to simulate the fact that particles which are slightly off the equatorial plane are compressed toward the equatorial plane as they are move inward. Here v is the particle's velocity that a detector would see and v_d is the guiding center velocity our virtual satellite would see, the factor v/v_d corrects for the difference since in a real detector flux is proportional to v (not v_d). The initial radial distribution for protons was modeled by

$$fr = [\frac{(L_0 - a_0)^{nl}}{L_0^{ml}}]/[\frac{(a_{0d} - a_0)^{nl}}{a_{0d}^{ml}}], \tag{5}$$

and for electrons was modeled by

$$fr = [\frac{(L_0 - a_0)^{nl} * (6.7)^{(eml-ml)}}{L_0^{eml}}]/[\frac{(a_{0d} - a_0)^{nl}}{a_{0d}^{ml}}], \tag{6}$$

where $a_0 = 3, nl = 4, ml = 9, a_{0d} = 6$, and $eml = ml + 800 * \sin(W_0/800)/55$ is for electrons with initial energy less than 1.1 MeV and azimuthal angle less than 125° or greater than 270° at the arrival of the shock, otherwise $eml = ml$. These parameters are chosen empirically to provide the initial distribution of the source

populations, which give, in conjunction with the model field, the simulated results closest in comparison with the observations. Solar energetic protons provide an abundant source population for this event. Protons were assumed to have a common radial dependence initially for all energies. When the shock impacted magnetosphere, the higher energetic electron fluxes at geosynchronous orbit decreased, which is due to the weaker source population of the high energy electrons (Li et al., 1993; Li et al., 1998). The radial dependence of electrons was more complicated and assumed to vary with energy, fewer energetic electrons at larger radial distance, as illustrated in Figure 4. The assumed initial distributions are consistent with measurements made by POLAR satellite at earlier times (Private comm., Richard Selesnick, 2000). Thus, given an initial particle distribution, we could obtain electron and proton fluxes and distributions for comparison with the LANL measurements. We have also incorporated the LANL detectors' responses and actual location and motion into our simulation.

Figure 4

Figure 5

Figure 6

Figures 5 and 6 show such comparisons for electrons and protons respectively. The left columns are LANL measurements and the right columns show our simulation results using the above model parameters. The initial enhancements of lower-energy electrons, all energy protons, and the decrease of higher-energy electrons at different satellites are qualitatively reproduced as the second peaks which are wider and higher. The following peaks (drift echoes) are mostly due to particles injected from the nightside. The drift echoes are more evident in the simulation than the measurements since we only consider equatorially mirroring particles, which have the same drift speeds for the same energies. The LANL measurements, however, are omni-directional (Belian et al., 1992), so particles with the same energies but different pitch angles have different drift speeds. The LANL measurements have a time resolution of 10 s while our simulated results have a time resolution of 60 s and the small fluctuations in the simulated results are due to the statistics of the finite number of particles.

In order to reproduce the injection from midnight, we had to model the time-varying field by a pulse covering a wide local time range, which is in contrast to the model field used to simulate an isolated substorm injection (Li et al., 1998), where the pulse was confined to a narrow local time (in that case, $k = 3$ in Eq. (1)) to simulate a dipolarization that usually occurs within a limited local time zone (Baker et al., 1996). So this

model field, due to its wide local time coverage, represents a more global field change on the nightside and thus can affect more highly energetic particles. The whole nightside magnetotail magnetic field enhanced following the arrival of an interplanetary shock as indicated by GOES-8 and GOES-10 observations. In our model we varied the velocity, v_0, between 80 and 200 km/s, the electric field amplitude, E_0, between 0.4 and 4 mV/m, and the local time dependence, c_1, between 0.2 and 1, and k, between 1 and 3. The criterion of good agreement with the measurements is to reproduce the observed particle fluxes. After numerous runs with different combinations of the parameters, we found that the chosen parameters reproduce both the electron and proton data best.

It should be noted that the modeled fields are not unique and the detailed features of the real fields are certainly more complicated than the model but the modeled parameters and our many attempts to reproduce the data by pulses of various widths and amplitudes show that the nightside injection is broad and involves fields over a large range of local time and radial distance. The agreement between the model and the data is of course not perfect. Our field model is very simple and we ignore many real features of the magnetosphere such as the overall convection electric field, pitch angle scattering, time variability of the source population other than that caused by our field changes, and non-dipole field effects. Our goal has been to focus on the time around the arrival of the shock and to show that there were in fact two injections.

It should also be noted that our model represents the electric and magnetic field at the magnetic equator. Most relevant to the model is the total inward motion of the magnetic flux which results in an enhancement of the magnetic field in both the model and observations, see Fig. 1 and 3. GOES-8 and GOES-10 were off the equator since their dominant magnetic field component in the observations is H_e (earthward). Had a satellite been at the equator, the dominant component of magnetic field would have been the H_p-component. Particles, because they mirror back and forth over the field line, sense the change over the whole field line which is best represented by the change at the equator. This difference should be taken into account when the modeled fields are compared with the actual measurements. Furthermore, the measured fields represent the change in fields at one point whereas the particles represent the change in the fields over distances of many R_E.

The sudden decrease of higher-energy electrons indicates a lack of source population at larger radial distances, as illustrated at Figure 4. The injection may look different at different radial distances. Figure 7 shows how a slight change in the radial distance may effect the simulation results. The shock injection (without the second injection from nightside) is shown at three virtual spacecraft aligning in local time with spacecraft 2 (LANL-097) but at smaller radial distances. We see a sudden enhancement rather than a decrease of the higher-energy electrons at smaller L-values. This is due to a change in the source population of the electrons at different radial distance. The second peaks of the electron fluxes, however, are always lower than the first peaks because of the dispersion in drifting around the Earth, from injection on the nightside.

Figure 7

Figure 8(a) shows the trajectory of one electron and one proton with 90° pitch angle at the equator. Both the electron and proton are energized and transported inward as they encounter the two pulse fields which modify their trajectories. Figure 8(b) and (d) show the time history of the radial distance and kinetic energy of the two particles.

Figure 8

Both pulse fields can energize particles and inject them into the inner magnetosphere while conserving their first adiabatic invariant. The energy gain of a particle can be understood as a result of its inward motion into a stronger background magnetic field and the increase of local magnetic field due to the pulse. Equivalently, with the guiding center approximation, the energy gain of a particle can also be thought to come from the two terms in Eq. (2). The first term $q\dot{\mathbf{R}}_{\perp} \cdot \mathbf{E}_w$ is the rate of increase of energy due to work done by the electric field on the guiding center, while the second term $(M_r/\gamma)(\partial B/\partial t)$ is due to the curl of $\mathbf{E}_w$ acting about the circle of gyration. The solid and dashed lines in Figure 8(c) are the rates of increase of energy (in units of keV/min) from the first term (solid line) and the second term (dotted line) in Eq. (2), respectively, for the electron described in Figure 8(a), (b) and (d).

Particle precipitation in wide local time regions observed from Polar/UVI imager

Figure 9

The two-pulse field model is also supported by the Polar UVI imager observation for the same time period. Figure 9 shows the global auroral images from Lyman-Birge-Hopfield (LBH) emissions obtained by the Polar UVI camera in the passband 170-190 nm (Torr et al., 1995). The absolute photon fluxes in this LBH band

are logarithmically scaled and displayed in the Apex magnetic coordinates (MLT and MLat) (Richmond, 1995). The top three images show the sequence of images for the isolated substorm event and the bottom three the sequence associated the interplanetary shock. The UVI camera was operating in a mode to obtain each auroral image in 36 s and telemeter every 3 minutes. The time indicated in each image indicates the start time of the auroral observation.

The image at 04:47:16 UT shows a small brightening in the 21 MLT sector which is the first indication that an auroral breakup was occurring. Approximately 3 minutes later, the spot at 21 MLT increased in size and precipitation intensified and at 04:53:24 UT, this breakup region spread in both latitude and longitude, joining the pre-existing auroral activity in the morning sector. This is a typical signature of an isolated substorm expansion process.

The brightenings in the image at 06:50:33 UT (which includes the shock arrival time of 06:51 UT) centered around the 21 MLT sector and on the dayside centered around 15 MLT, are associated with the shock induced precipitation. Note also the weak but significant auroral precipitation occurring from midnight to past 03 MLT. The 06:53:37 UT image shows that the dayside precipitation became more intense than the dusk side and while the dusk side precipitation covered the 60-70° MLat, the dayside precipitation occurred at higher MLAT, 75°. The image three minutes later (06:56:41 UT) shows an intense auroral expansion both poleward and equatorward. The dayside precipitation by then had subsided.

Auroral precipitation driven by the interplanetary shock shows distinctly different features from usual substorm expansion events. First, the shock induced precipitation occurs over a wide region of MLT and Mlat. This indicates that the source of the electrons precipitating during and after the shock comes from a larger region of the magnetosphere. Second, intense precipitation is induced on the dayside. The morphology of the precipitation region and the “independent” behavior of the auroral features indicate that the source of the day side precipitation is distinct from the others. Similar auroral features after a pressure pulse on Jan. 10, 1997 were reported by Zesta et al. [2000].

Summary and Conclusions

An injection was observed almost simultaneously at 6:51 UT by all three LANL sensors at different local times, coincident with the arrival of an interplanetary shock, which was clearly observed upstream in the solar wind. The simultaneous enhancement of particle fluxes suggest a global compression. The sudden decrease of higher-energy electrons indicate a lack of their source population at larger radial distances.

The characteristics of this event, a second sudden enhancement over a wide local time region within 10-min following the shock impact, probably fall into the class of events previously documented by Kokubun et al. [1977]. However, in that study more modest solar wind triggers were shown to cause substorms if the magnetosphere was preconditioned by a previous southward interplanetary magnetic field. The most interesting and significant result of this study is that the whole nightside magnetic field enhanced about ten minutes after the initial shock compression, injecting energetic electrons and ions into the inner magnetosphere. In order to reproduce the particle injections observed at geosynchronous orbit, we had to model a magnetic field enhancement over the whole nightside with the peak magnitude at midnight as shown in Figure 3. This proposed field configuration change from modeling the particle data at geosynchronous orbit is supported by the Polar UVI imager observation for the same time period. This magnetic field change is in contrast to a typical isolated substorm onset during which a dipolarization is initiated around local midnight and later spreads in azimuth in both directions but still within a limited local time range (substorm current wedge). If this event is considered a substorm it shows that solar wind triggering is very important in initiating a substorm and even in determining the size of the substorm because for the given solar wind conditions one would not normally have expected a substorm. The interplanetary magnetic field had only turned slightly southward just before the shock but not for a long enough time for even a modest substorm to form which usually requires a growth phase of half an hour or so. The fact that the magnetotail undergoes a rapid global reconfiguration right after the arrival of the shock and consequently injects energetic particles into the inner magnetosphere within a few minutes suggest that the magnetotail can release a significant amount of energy even when it is not particularly well preconditioned if the solar wind trigger is large enough.

Other events such as Jan. 10, 1997 (Zesta et al., 2000), Sept. 24, 1998 (Russell et al., 2000) and Feb. 18, 1999 show a similar scenario regarding particle injections and nightside magnetic field configuration changes.

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Figure Captions

Figure 1. Various parameters plotted vs. time on August, 1998. From 04:30 UT to 09:30 UT, in GSE coordinates WIND moved from (116,-22,-8) to (118, -21, -8) R_E and Geotail moved from (26, 6, 0) to (23, 9, 0) R_E. The panels are: (a), (b), (c) for solar wind velocity, V_X, ion density, N_i, and dynamic pressure, P_{sw}, (every 2 min) from WIND [courtesy of K. Ogilvie]; (d) for Bz component (in GSE coordinate) and magnitude (dotted line) of the interplanetary magnetic field (IMF) (every 1 min) from WIND [courtesy of R. Lepping]; (e), (f) for the magnitude (dotted line) and Bx, By (dotted line), Bz components of the IMF (every 1 min) from Geotail [courtesy of Kokubun]; (g), (h), (i) for solar wind velocity, V_X, ion density, N_i, and dynamic pressure, ρV_X^2 [courtesy of Frank]; (j),(k),(l) for magnitude and the three components of the magnetic field

(H_p: parallel to the Earth's magnetic field dipole axis, H_e: earthward, H_n: eastward) from GOES-8 (every 0.5 sec), LT=UT-5:04.

Figure 2. Differential fluxes (#/s-sr-cm^2-keV) of electrons and protons from LANL observations in the early Aug. 26, 1998. Number 1, 2, and 3 correspond to spacecraft 1991-080 (LT=UT+0:35), 1990-97a (LT=UT+4:37), and 1994-084 (LT=UT+6:54) respectively. The top diagram indicates the LT positions of the spacecraft including GOES-8(G- 8) around 6:50 UT.

Figure 3. Electric field, E_ϕ, and magnetic field, B_z, from the two-pulse model in the equatorial plane at geosynchronous orbit at different locations.

Figure 4. Radial dependence of initial particle distribution for protons and electrons.

Figure 5. Differential fluxes of electrons from LANL observations in the left column; the simulation results from the two-pulse model are shown in the right column.

Figure 6. Same as Figure 5 except for protons.

Figure 7. The same simulation results of the single pulse model but plotted at three virtual spacecraft synchronizing in local time with spacecraft 2 (LANL-097) but at smaller radial distances.

Figure 8. (a) trajectory of an electron (red) and a proton (green) with 90° pitch angle initially placed in the equatorial plane with $r_0 = 8.8R_E$, $W_0 = 200$ keV, and $\phi_0 = 145°$ (electron) and $r_0 = 8.3R_E$, $W_0 = 135$ keV, and $\phi_0 = 128°$ (green). The dotted circle represents r=6.6 R_E. (b) and (d) radial distance and kinetic energy representing the time history of the two electrons. (c) The rate of energy gain for the electron in discussion, from the first term (solid line) and the second term (dashed line) in Eq. (2).

Figure 9. Selected UVI images during the two events of interest: an isolated substorm onset around 4:50 UT and a shock impact around 6:51 UT (see Figures 1 and 2 for these two events).