Poleward progressing quasiperiodic disturbances at cusp latitudes: The role of wave processes

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Abstract. Observations from various magnetometer networks, including Magnetometer Array for Cusp and Cleft Studies (MACCS), Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS), the Greenland Coastal Chain, and the U.S./Russia Antarctic Array, made on January 5, 1995, show an event of very long period pulsations (30–to 40-min period) in the cusp region. Pulsations were driven by quasiperiodic Interplanetary Magnetic Field (IMF) $B_y$ variations which were observed by the Wind spacecraft. Disturbances of this type are commonly interpreted as poleward moving, east-west oriented ionospheric currents (e.g., intensification of the DPY current system), stimulated by reconnection processes at the dayside magnetopause. However, the temporal/spatial, ground-based structure of such disturbances can better be described if this picture is augmented by the inclusion of transient wave processes, for example, distortions of the Alfvén phase front, transmitting a disturbance from an assumed reconnection region to the ionosphere. In general, this type of disturbance, which we suggest calling $P_{DYP}$ pulsations, is shown to be a manifestation of the modulation of the high-latitude ionosphere electrodynamics by a large-scale Alfvén wave in the solar wind under favorable IMF orientation.

1. Introduction

Variations of the geomagnetic field with typical quasi-periods of about several tens of minutes are a boundary phenomenon, lying between the ULF range and the timescale of convection disturbances. Perhaps that is the reason why both the global electrodynamics community and the ultra-low frequency (ULF) community have studied quasiperiodic variations with that timescale independently for a long time.

In a number of studies of ionospheric electrodynamics, various instruments have been reported to have observed dayside variations at high latitudes with such typical timescales. The quasiperiodic disturbances detected by ground-based magnetometers are usually called “poleward progressing ionospheric convection disturbances.” These events show a close temporal association between Interplanetary Magnetic Field (IMF) $B_y$ variations and progressing perturbations in the $H$ and $Z$ components of the geomagnetic field at polar latitudes. A typical example is the August 2-3, 1991, event thoroughly studied in several papers [e.g., Clauer et al., 1995; Stauning, 1995]. During this event the IMF $B_z$ component measured by the IMP 8 spacecraft remained strongly southward, whereas the IMF $B_y$ component varied nearly periodically with a period of ~25–30 min. The observed ground magnetic disturbances reached amplitudes ~30 times larger than those of the IMF variations.

Clauer et al. [1995] interpreted these observations as the signature of a poleward propagating DYP current system, intensified in association with the reconnection processes occurring at the dayside magnetopause and stimulated by the IMF $B_y$ component. They assumed that the DYP current system is driven by a meridional electric field imposed between longitudinal sheets of the field-aligned currents placed along the poleward and equatorward “walls” of the cleft. The global context of the polar ionospheric convection pattern for this event was given by Papitashvili et al. [1995], who employed the IZMEM (Russian abbreviation for the Institute of Terrestrial Magnetism Electrodynamic Model) empirical model of ionospheric electrodynamics. The modeled global convection patterns showed good agreement with the Sondrestrom radar observations of the ionospheric convection in the cusp region modulated by IMF $B_y$, though the authors do not report poleward progression of the modeled or observed convection flow in the radar’s field of view. Stauning [1995] suggested that a probable connection between IMF $B_y$ variations and polar geomagnetic variations might be established.
by the field-aligned currents flowing along merged interplanetary and geomagnetic field lines in the open magnetosphere.

However, none of these authors considered the possible wave nature of these pulsations, - they rather treated them as distinct, progressing enhancements of the ionospheric current system. The pulsations were attributed to variations in the east-west ionospheric current sheet elongated in longitude \( \sim 3 \) hours with limited north-south extent \(( \sim 11^\circ)\) and propagating poleward with a velocity of \( \sim 0.5-1 \) km/s near the dayside polar cusp. The magnetic pulsations were accompanied by the poleward propagation of auroral intensification, riometer absorption enhancements, and ionospheric plasma convection.

On the other hand, the ULF community usually considers these disturbances as very long period (VLP) pulsations, the lowest frequency ULF phenomena in the terrestrial magnetosphere. Statistical properties of the VLP variations were extensively studied by O. Bolshakova, N. Kleimenova, and coworkers in a series of papers, utilizing photographic and paper chart magnetograms from a number of Greenlandic and Antarctic stations. Kleimenova et al. [1986] noticed the following specific features of VLP pulsations: quasiperiods of 20- to 40-min, peak-to-peak amplitudes of 80-400 nT, duration of \( \sim 3 \) cycles, and specific polarization along the \( H \) and \( Z \) components. The pulsations were mainly observed at \( K_p=4-5 \), reaching maximal intensity at \( 75^0-77.5^0 \) geomagnetic latitudes. VLP pulsations are rather rare phenomena, and only one to two events per month are observed. Their occurrence frequency reaches maximum near noon, and the VLP events are most frequent in summer. They have been detected very seldom in the Southern Hemisphere.

The VLP pulsations were observed to be a localized phenomenon: in contrast to auroral bay-like DP 2 disturbances, which can be traced down to the Earth’s equator, these pulsations have been observed only at latitudes of dayside cusp. Bolshakova et al. [1987] have noticed the poleward movement of VLP pulsations with an apparent velocity of \( 1-2 \) km/s. Statistically, the VLP pulsation maximum shifts with local time and does not follow the same geomagnetic latitude [Bolshakova et al., 1989].

In these earlier studies, IMF hourly means have been used for the IMF/ground comparisons. It was noticed that the most favorable IMF orientation for the occurrence of VLP pulsations was southward IMF. About 90% of the VLP events were observed during IMF \( B_y > 0 \), which led Kleimenova et al. [1986] to suggest that VLP are generated by fluctuations of the \( DPY \) current system. The idea that dayside reconnection processes could stimulate VLP has also been proposed by Bolshakova et al. [1988] and Kurazhkovska [1990].

Even from this brief comparison of the VLP properties and features of the poleward progressing ionospheric \( DPY \) disturbances, we may conclude that two groups of researchers have actually studied the same phenomenon independently. To put this phenomenon in the context of existing nomenclature of ULF waves, we suggest terming VLP pulsations as "\( PDy \) pulsations." This name is in accordance with the existing classification scheme and is more appropriate. For example, quasiperiodic disturbances with periods longer than typical Pc5 band, stimulated by a storm sudden commencement (SC), are named \( PS_c6 \) [Saito, 1976]. The suggested name, \( PDy \), indicates that these pulsations \(( P) \) have periods beyond the Pc5 band \(( 6) \) and are associated with an intensification of the \( DPY \) current system at cusp latitudes.

In this paper we will analyze in detail one event of this type and show that the description of \( PDy \) as a poleward moving oscillatory current is not sufficient to interpret all the features of the observed temporal/spatial structures. We propose that a more adequate description of the \( PDy \) disturbances can be suggested when the entire picture is augmented by the inclusion of transient wave processes.

2. Experimental Facilities

This study is based on data from a global array of magnetic stations at high latitudes, including the following:

The Canadian Auroral Network for the OPEN program Unified Study (CANOPUS) (http://www.dsp-agency.ca/www/canopus-home.html) is equipped with automatic stations for magnetic and optical observations of the auroral oval in west-central Canada. The sampling period for magnetic measurements is 5 s.

The Magnetometer Array for Cusp and Cleft Studies (MACCS) (http://space.augsburg.edu/space/) is a network of identical fluxgate magnetometers with one station in the polar cap and others along geomagnetic latitudes \( \sim 79^0 \) and \( \sim 75^0 \). The data used are 5-s averages of data originally sampled at 0.5- to 1-s intervals.

The 210 Magnetic Meridian chain (http://tdb2.stelab.nagoya-u.ac.jp/mm210/) comprises magnetic stations with fluxgate magnetometers with 1-s sampling period and all-sky auroral imagers in northern Siberia. The range of latitudes covered from the equator up to \( 65^0 \) is well suited for monitoring substorm and auroral activity.

The Greenland magnetometer network (http://www.dmi.dk/projects/chain/) consists of two latitudinal chains of stations with 20-sec sampling period along the west and east coasts.

The Magnetometer Array at Greenland Ice Cap (MAGIC) (http://www.sprl.unic.edu/MIST/) is an array which was deployed to augment the Greenland coastal chains. The data provided were interpolated and merged into the 20-s Greenland network database.

For conjugate observations the U.S./Russia Antarctic array of magnetometers (http://www.sprl.unic.edu/MIST/) with 10-s time resolution were utilized. The U.S. Automatic Geophysical Observatories in Antarctica suffered from data gaps during this period. Geographic and geomagnetic coordinates of the stations used in this study are given in Table 1; a map showing
Table 1. High-Latitude Stations for epoch 1995

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Magnetometer Array for Cusp and Clej Studies (MACCS)

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U.S./Russia Antarctic Array

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Greenland West Coastal Array

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Magnetometer Array at Greenland Ice Cap (MAGIC)

3. PDPY6 Pulsations: Case Study of the January 5, 1995, Event

Very long period (~ 30–40 min) high-latitude oscillations are observed on the dayside at all networks from ~ 1555 until ~ 1805 UT. Figure 2 shows a sample from the Greenland west coast stations. These oscillations seem to suppress broadband Pc5 pulsations that commonly have maximal intensity during the prenoon and noon hours [Engelbreton et al., 1996]. The fading of Pc5 activity can be related to the effect of the suppression of Pc5 activity by the onset of a nightside storm, which started at 1520 UT according to observations along the 210 Magnetic Meridian network. This effect was described in greater detail by Pilipenko et al. [1998]. At all the networks the PDPY6 are most clearly seen in the H component. They are less evident in the Z component and even smaller in the D component (not shown). These long-period quasi-periodic variations are a typical example of the phenomena we named PDPY6 pulsations. Now we examine the global spatial structure of this particular event along the meridional and azimuthal profiles composed from the stations under study.

3.1. Global Meridional Structure of PDPY6 at Different Longitudes

Along the Greenland west coast profile (geomagnetic longitude λ ≈ 40°E), a wide maximum of PDPY6 intensity is observed in the range of corrected geomagnetic latitudes (CGM) between ~ 72°–74° (stations from SKT to STF) with gradual decrease poleward (Figure 2). Magnitudes of peak-to-peak variations reach a max-
imum of $\sim 180$ nT. The $P_{DPY6}$ pulsations appear to originate at latitudes that are probably lower than the equatorward cusp boundary.

Along the east coast of Greenland ($\lambda \sim 80^0W$), $P_{DPY6}$ pulsations are hardly visible and are not shown. At the MAGIC network at $\sim 76^0-77^0$ in central Greenland ($\lambda \sim 66^0E$), weak traces of $P_{DPY6}$ pulsations were detected (not shown).

The combined profile TA-GH-RN-ES-CC-BA-GI along the geomagnetic longitude $\lambda \sim 30^0W$ (Figure 3), composed of CANOPUS and MACCS stations, is in the prenoon sector when the $P_{DPY6}$ occurs. Along this profile, the maximal $P_{DPY6}$ magnitudes, up to 300 nT, are observed at latitudes $\sim 72.0^0-73.7^0$ (stations RN and ES).

3.2. Global Azimuthal Structure of $P_{DPY6}$

The longitudinal structure of $P_{DPY6}$ can be seen along the profile at geomagnetic latitudes $75^0 \pm 1.5^0$ formed by the following stations from MAGIC, Greenland, MACCS, and CANOPUS networks: MCE-ATU-CD-CH-RN-CO, covering the range of geomagnetic longitudes from $66^0E$ to $61^0W$ (Figure 4). The data from MACCS/CANOPUS stations have been decimated to a common time step of 20 s consistent with Greenland stations. At the Greenland east coast (station DNB at $80^0E$) and at most westward CANOPUS station, DA ($90^0W$), the $P_{DPY6}$ signals fade away.

The $P_{DPY6}$ activity is extended in longitude from $39^0E$ (ATU) to $61^0W$ (CO); that is their azimuthal scale is $\sim 100^0$. The maximum of the $P_{DPY6}$ amplitude is found in the sector $1^0E$ to $30^0W$ (CD-CH-RN), in the center of the MACCS/CANOPUS network, at prenoon hours.

3.3. Local Polarization Structure and Propagation Features

Now we consider in greater detail local features of the $P_{DPY6}$ spatial structure in the region of their maximal intensity. From the MACCS network a limited latitudinal profile can be formed from stations IG-RB-CH along $\lambda \sim 350^0E = 10^0W$, covering the range of latitudes $79.4^0-74.8^0$ (Figure 5). Maximal intensity is observed at the lowest latitude station, CH.

The time delay of $\sim 4$ min between CH and RB, separated in latitude by $2.1^0$ (which can be seen in Figure 5, top), corresponds to an apparent poleward propagation velocity $V \sim 1$ km/s. There is an even higher apparent propagation velocity in the same latitude range in the $Z$ component (Figure 5b). At the same time, between distant stations, that is, IG and RB, no evident propagation can be recognized (Figure 5).

The azimuthal propagation can be best estimated from data from the interval 1600-1830 UT from the stations CD and CH, located at the same geomagnetic lat-
Figure 2. The meridional structure of $P_{DFY}$6 pulsations ($H$ component in corrected geomagnetic coordinates) along the Greenland west coast chain, observed on January 5, 1995, 1300-1900 UT.

itude and longitudinally separated by 12° or 319 km. During this interval both stations are near local magnetic noon (at CD this corresponds to 1645 UT, and at CH this corresponds to 1730 UT), where the disturbance is very intense Figure 6. The cross-correlation function of the signals at these stations reaches a maximum of 0.96 for a time delay of 70 s, indicating apparent antisunward propagation with a velocity $V \approx 4.6$ km/s. This velocity is in the range of typical east-west TCV velocities. At the same time, with the given time accuracy and sampling rate, no regular east-west propagation throughout the longitudinal profile between stations laying far from the pulsations “epicenter” is evident (Figure 4).

Variations of the structure of $P_{DFY}$6 in the vertical plane ($H$, $Z$) along the meridian can be studied in greater detail with the combined CANOPUS/MACCS profile (Figure 7). The data in the interval 1630-1730 UT were detrended and low-pass filtered with a cutoff frequency of 5 mHz. Inspection of these plots shows that the $H$ component decreases away from the $P_{DFY}$6 “epicenter” (around RN) faster than the $Z$ component does (e.g., at TA no traces of pulsations in the $H$ component are seen, whereas in the $Z$ component they are noticeable).

It should be noted that there is a phase inversion of the $Z$ component, as can be seen from a comparison of $Z$ components at TA, GH, on one hand, and CC, BA, on the other hand, around 1715 UT. Accordingly, the relationship between north-south ($H$) and vertical ($Z$) field components varies from out of phase at GH to in phase at ES, CC, and BA.

These in-phase and out-of-phase relationships hold rather approximately, and some small phase shifts between $H$ and $Z$ components are noticeable. Moreover, near the maximum of the $H$ component (at RN) the $Z$
component amplitude does not tend to be zero but remains finite (see also station CH in Figure 5). Though, in principle, a point where the amplitude of the $Z$ component of the pulsations is zero can be missed owing to sparse network spacing. However, the similar behavior of these components can be seen for the event considered by Clauer et al. [1995] along the more dense Greenland west coast chain. Thus the observed amplitude/phase relationships in the vertical plane do not fit well the notion of quasi-steady variations of an ionospheric current system.

3.4. Conjugate Observations

From the available Antarctic magnetic stations, VOS is approximately conjugate to SVS on the Greenland west coast, and SUD is conjugate to NRD on the Greenland east coast. A possible mismatch in the stations conjugacy is of little relevance, because oscillations are practically coherent spatially throughout a large area, except for the region near the source, where small time delays exist owing to the apparent poleward and westward propagation. As might be expected, the $P_{Dp}$ oscillations are hardly evident at SUD and NRD.
Comparison of the magnetic $H$ components from VOS and SVS, given in Figure 8, shows that the oscillations are in antiphase between Northern and Southern hemispheres. A detailed comparison of the $H$ components from the conjugate stations shows that the first, most readily discernible peak of disturbance arrives earlier at SVS than it does at VOS by $\sim 5$ min.

4. Solar Wind and IMF Observations

In the interval analyzed the Wind spacecraft was upstream from Earth (in the GSM coordinate system $X \simeq 106 \, R_E$, $Y \simeq -75 \, R_E$, and $Z \simeq -10 \, R_E$). The spacecraft recorded a steady solar wind flow with velocity $V_{sw} \simeq 630 \pm 20 \, \text{km/s}$. At 1405 and 1500 UT the satellite detected changes of the IMF $B_z$ component from northward to southward (Figure 9d). This persistent negative IMF $B_z$ was the apparent cause of the substorm that occurred at 1520 UT.

On the background of the southward IMF, quasiperiodic oscillations in the IMF $B_y$ component appear at $\sim 1525$ UT (Figure 9c, thick line), and their peak-to-peak amplitude reaches 11 nT. The magnetic field oscillations are accompanied by simultaneous in-phase oscillations of the corresponding solar wind plasma velocity component, $V_{swy}$ (Figure 9c, dashed line), with peak-to-peak amplitude $\sim 80$ km/s. However, these large-amplitude oscillations do not disturb the magnitude of total mag-
netic field, $B \simeq 6$ nT, and plasma density, $N \simeq 4 \text{ cm}^{-3}$ (Figure 9a). The observed features of these oscillations indicate that they are caused by a large-scale Alfvén wave propagating through the solar wind.

The 30- to 40-min periods of the IMF variations are similar to those of the $P_{D P Y}$ pulsations recorded on the ground. More detailed comparison of the Wind observations and ground magnetometer data (station CD), given in Figure 10, shows that the wave forms of the IMF $B_y$ variations are similar to the $P_{D P Y}$ pulsations recorded on the ground. The characteristic peaks of quasiperiodic IMF $B_y$ variations are some 20 min ahead of the corresponding features of $P_{D P Y}$ on the ground. This delay fits the expected ballistic travel time from Wind to the nominal bow shock, for example, $\sim X/V_z \simeq 94 R_E/630 \text{ km/s} \simeq 15.7 \text{ min}$.

Comparison of the Wind observations and ground magnetograms also indicates that rapid variations of

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**Figure 5.** The latitudinal structure and apparent poleward propagation of the (top) $P_{D P Y}$ $H$ component and (bottom) $Z$ component. Both components are observed along the MACCS meridional profile ($\sim 10^9 \text{W}$) on January 5, 1995, 1400-1900 UT. The dotted vertical line is the reference time mark. Total ordinate scale is 400 nT; scale between ticks is 100 nT. Local magnetic noon is marked with a triangle.
IMF $B_y$ with timescales much less than 10 min do not produce a response on the ground. For example, there is no ground-based response to short-lived “blips” in the IMF at $\sim 1520$ UT and to short-lived fluctuations superimposed on the $B_y$ variations. This fact accords the low-pass filtering features of the IMF control on ground magnetic disturbances found by Murr and Hughes [1998]. It should be mentioned also that the southward IMF changed to northward during two short intervals starting on $\sim 1700$ and $\sim 1715$ UT (Figure 9), but the quasi-periodic modulation of geomagnetic field still remained during these intervals (Figure 10).

5. Discussion

In the day-side hours on January 5, 1995, quasi-periodic long-period oscillations with an apparent period of $\sim 30$–40 min were observed. They were polarized mainly in the $H-Z$ plane, and their peak-to-peak amplitudes reached maximum values of $\sim 400$ nT near $73^0-75^0$ geomagnetic latitude. The polarization of these pulsations indicates that they are quasi-periodic variations of an azimuthal ionospheric current. The time shifts between different MACCS stations correspond to an antisunward propagation, indicating that the entire structure is dragging by the solar wind flow around the magnetosphere. The combined CANOPUS/MACCS network reveals the poleward propagation near the “epicenter” of the signal. The properties of these oscillations are consistent with those of disturbances classified as poleward progressing $DPY$ disturbances, and we have termed them $DPY$ pulsations.

5.1. $DPY$ Pulsations as Field Line Oscillations

Persistent occurrence of periodic disturbances might indicate the existence of some natural resonant mechanism that produces pulsations with a particular period as a consequence of an external impact. The best known resonant phenomenon of this kind is the magnetospheric Alfvén resonance of the geomagnetic field lines. In early studies of the $DPY$ (VLP) pulsations it was suggested that they are the result of field line oscillations near the boundary of the magnetosphere [Bolskaya et al., 1987, 1989]. In fact, some observational features of the $DPY$ structure fit well with the typical spatial structure of Pc3–Pc5 ULF waves in the resonant region, including asymmetric polarization of the horizontal disturbance with $H \gg D$, an apparent poleward phase velocity, and nonzero amplitude of the $Z$ component near the pulsation’s maximum. However, typical $DPY$ periods, more than 20 min, are longer than periods of any possible field line oscillations according to the existing MHD models (e.g., at $L = 10$ the period of the fundamental mode is $T_A \approx 10$ min even for a low Alfvén velocity, $V_A = 300$ km/s). Invoking a non-symmetric quarter-wave mode between conjugate sunlit and dark ionospheres may increase this estimate by a factor of 2, but even that would not be enough.

Moreover, if we assume that $DPY$ pulsations represent a standing Alfvén mode between conductive ionospheres, as most ULF waves do, the $H$ components of the fundamental mode must be in phase. The reverse relationship observed between conjugate stations in Greenland and Antarctica requires that $DPY$ be an even mode (with a node of field line displacement at the
magnetospheric equator). Thus the observed oscillation cannot be a fundamental (odd) mode but, at most, a second harmonic. This fact makes the interpretation of $P_{DPIV}$ as a standing Alfven wave even more difficult.

5.2. Generation Mechanism

The event studied here shows an example of the intense modulation of the magnetosphere-ionosphere current systems by relatively moderate IMF variations. The southward turning of $B_z$ causes an enhancement of the westward electrojet, suppression of Pc5 turbulence, and finally excitation of a substorm, while the quasiperiodic variations of $B_y$ induce 30–40 times more intense $P_{DPIV}$ pulsations.

HF radars measured poleward moving patches of antisunward flow with a typical recurrence rate of 7-8 min.
These regions were named "pulsed ionospheric flows" (PIF), and it was suggested that they are associated with flux transfer events (FTE) [Provan et al., 1999]. The occurrence region of these transient flows was found to depend on the sense of the IMF \( B_y \) component. Similar disturbances in the auroral intensity recurring at 5-8 min during intervals of negative IMF \( B_z \) were named "poleward moving auroral forms" (PMAFs) [Oieroset et al., 1997; Sandholt and Farrugia, 1999]. Observations of poleward progressing ionospheric \( DPY \) currents (Hall currents modulated by the IMF \( B_y \)) and riometer absorption enhancements, presented by Prikryl et al. [1999], indicate their possible association with \( P_c5 \) field line resonances. The authors conclude that large-amplitude Alfvén waves in the solar wind might modulate the subsolar magnetic reconnection in pulses that result in ionospheric convection flow bursts and drive field line resonances.

Thus the entire "swo" of the observed dayside transient phenomena could be different appearances of the same process: quasiperiodic bursts of enhanced reconnection or pulsed magnetopause reconnection. We speculate that the short-lived sporadic poleward progressing disturbances (e.g., PIF, PMAF, etc.) are the result of spontaneous reconnection, whereas the regular quasiperiodic variations (such as \( P_{DPY} \) 6 pulsations) are the oscillatory response of the magnetosphere to periodic forcing by the IMF-driven reconnection.

The efficiency of Alfvén wave (or field-aligned current) generation during reconnection has been studied by Ma and Lee [1999] by means of a three-dimensional numerical model. They found that the induced field-aligned currents are not only confined to the reconnected magnetic flux region with a scale \( a \) but that a considerable amount (\( \sim 40\% \)) of these currents flows on closed field lines. The excitation rate from the upper theoretical limit, \( \sim B_0/\mu_0 a \), was found to be \( \sim 4\% \), which turns out to be sufficient to produce above the ionosphere the magnitudes of field-aligned currents which fit observations.

From the viewpoint of reconnection models, the observed relationship between variations in conjugate ionospheres is just as expected. Field-aligned currents should flow in the same direction relative to the magnetic field direction in both hemispheres; thus corresponding Hall currents should produce opposite effects in conjugate hemispheres. Additionally, \( B_y \)-driven ionospheric convection patterns in conjugate ionospheres should be shifted in opposite directions.

The conjugate observations indicate a small but discernible difference in the \( P_{DPY} \) 6 arrival times in conjugate hemispheres by \( \sim 5 \) min. Assuming that the analyzed disturbance is actually a transient Alfvén-type signal and not a standing mode, this time delay can be explained as being a consequence of the dominant source region (merging site) on the magnetopause being closer to the northern ionosphere than to the southern ionosphere. This is because of the sunward orientation of \( B_z \) (\( > 0 \)) during this interval. Thus the most likely reconnection site of antiparallel IMF and geomagnetic field is much closer to the northern polar cap than to the southern polar cap. However, the mentioned above nonconjugacy of \( B_y \)-driven ionospheric convection may affect significantly the particular estimate of the source shift from the magnetospheric equator.

Some additional arguments in favor of the Alfvénic nature of the quasiperiodic disturbance detected by Wind in the solar wind can be mentioned. From the MHD equations for cold incompressible plasma motions, the following relationship between plasma velocity \( V \) and magnetic field component \( B \) of the disturbance can be obtained:
Figure 9. (a-d) Interplanetary magnetic field and solar wind plasma observations by the Wind satellite on January 5, 1995, 1400-1900 UT. Left-hand scale shows total IMF magnetic field $B$ (nT) and its components $B_x$ (nT), $B_y$ (nT), and $B_z$ (nT) (thick lines); right-hand scale shows plasma density $N$ (cm$^{-3}$) and components $V_x$ (km/s) and $V_y$ (km/s) of the solar wind velocity (thin lines).

\[ M_N \frac{\partial \mathbf{V}}{\partial t} = \frac{1}{4\pi} (\mathbf{B}_0 \nabla) \mathbf{B}. \]

From this equation the relationship between the relative disturbances of plasma velocity and magnetic field produced by an Alfvén wave can be derived

\[ \mathbf{V} = \mp \frac{\mathbf{B}}{V_A}. \]

Here the upper (lower) sign refers to the propagation direction of an Alfvén wave according to the undisturbed magnetic field direction: $\mathbf{k} \cdot \mathbf{B} > 0 (< 0)$. For $N = 4$ cm$^{-3}$ and $B_0 = 6$ nT (i.e. $V_A \approx 44$ km/s), the magnitudes of the oscillatory disturbance in the solar wind fit well this simple relationship, for example, $V/V_A \approx B/B_0 \approx 0.9$.

As a possible working scenario, we may assume that the observed quasiperiodic variations of the IMF are,
Figure 10. Variations of the IMF $B_z$ and $B_y$ components and the response on the ground at station CD, from 1400 to 1900 UT, January 5, 1995.

In fact, large-scale Alfvén waves propagating outward through the solar wind [Tsurutani and Ho, 1999]. Then, within a reconnected flux tube the field-aligned currents from a solar wind disturbance can penetrate directly into the magnetosphere, as depicted in Figure 11.

It is possible that the higher-frequency Alfvén-type disturbances, whose field-aligned scales, $\sim k_\perp^{-1}$, are comparable to the curvature radius $R$ of a reconnected field line, will be substantially reflected. This critical frequency can be estimated as $\omega \simeq k_\parallel V_A \simeq V_A / R$. According to this simple estimate under the assumption that $R \simeq 1 R_E$ and $V_A \simeq 100$ km/s, the penetration into the magnetosphere of the IMF fluctuations with periods $\leq 6$ min could be substantially hampered owing to wave reflection at a sharply bent field line.

6. Model of Transient Ionospheric Response to Incident Alfvén Disturbance

The assumption that $P_{DHY}$ are simply the result of poleward progressing east-west Hall currents, although
it fits the basic features of $P_{DPY6}$, cannot explain some important details of $P_{DPY6}$ structure. As the current sheet (entire DPY current system) moves directly over a station, the $H$ component perturbation should be maximal, whereas the perturbation of $Z$ must tend to zero, having opposite signs at the northern and southern edges of the sheet. In fact, the $Z$ component perturbation seems to nowhere drop to zero near the latitudes with the intense $H$ component disturbance. More importantly, as will be shown below, a simple poleward motion of the ionospheric current cannot produce temporal variations on the ground which fit the observations. The occurrence of phase shifts between the stations and between the components further indicate that the magnetostatic fields of ionospheric currents cannot produce all the features of $P_{DPY6}$ structure.

We suppose that the observed time shifts along the meridian may be caused by a dependence of Alfvén transit times $T_A$ on spatial coordinates rather than an actual propagation pattern along the ionosphere. Realistic gradients of $T_A$ may provide apparent propagation velocities of the same order as those observed.

Let the disturbance propagation time from the equator to the ionosphere, $\tau$, depend on the radial distance $L$ and geomagnetic longitude $\Lambda$; that is, $\tau = \tau(L, \Lambda)$. Transient disturbances of the field-aligned currents excited near the magnetospheric equator or penetrating from the solar wind will reach the ionosphere at different latitudes at different times owing to the $\tau(L)$ dependence, as illustrated in Figure 11. As a result, the time delay $\Delta \tau$ to be observed between ground responses at different $L$ values is

$$\Delta \tau(L) = \tau(L_2, \Lambda) - \tau(L_1, \Lambda) \propto \frac{\partial \tau}{\partial L} \Delta L.$$  

In the outer magnetosphere, where $\partial \tau/\partial L > 0$, the observed time delay should correspond to an apparent poleward propagation. Assuming a dipole-like geometry of the geomagnetic field, the ground projection of an apparent phase propagation velocity in the latitudinal direction can be estimated as

$$V = \frac{2}{L\sqrt{L - 1}} \frac{l_A}{T_{A}},$$  

where $l_A = (\partial T_A/\partial r)^{-1}$ is a scale of the Alfvén period $T_A$ inhomogeneity near the magnetospheric equator ($r \approx L R_E$). For $l_A = 2 R_E$ and $T_A = 500$ s the relationship (1) gives at $L = 10$ an estimate of propagation velocity $V \approx 1.7$ km/s. This estimate fits by order of magnitude the observed poleward velocities.

7. Model of Progressing Ionospheric Current

In order to present a possible spatial-temporal distribution of the amplitudes and phases of magnetic disturbances on the ground, we consider the following simple model, illustrated in Figure 12. This model takes into account basic features of the wave scenario described above. A geomagnetic field $B_0$ is directed vertically down as in the Northern Hemisphere. The ionosphere is a thin current sheet with laterally homogeneous height-integrated anisotropic conductivity $\Sigma$ at an altitude $z = -h$. To account for the latitude-dependent phase delay of the front of the Alfvén disturbance impinging on the ionosphere, we introduce the time delay $\tau(x)$. The north-south component of the electric field $E_x$ of the incident disturbance at the ionosphere level ($z = -h$) can be written as

$$E_x^{(i)}(x, t) = E_0 A(x) F[t - \tau(x)],$$

where $F[t - \tau(x)]$ is the time variation at a particular $x$, $E_0$ is the amplitude of the incident signal, and $A(x)$ is the normalized distribution of the electric field along the ionosphere.

The total electric field in the ionosphere is the sum of the incident and reflected waves, namely,

$$E_x(x, z = -h, t) = (1 - R) E_0 A(x) F[t - \tau(x)],$$

infinite in the east-west (Y) direction. The Hall current produces a magnetic disturbance on the ground with the following components:

\[
B_x(X, t) = \frac{\mu_0}{2\pi} \int_{-d/2}^{d/2} \frac{J_H(X_1, t)}{1 + (X - X_1)^2} dX_1,
\]

\[
B_z(X, t) = -\frac{\mu_0}{2\pi} \int_{-d/2}^{d/2} \frac{(X - X_1)J_H(X_1, t)}{1 + (X - X_1)^2} dX_1.
\]

Here and further, all distances are normalized to the height \(h\) of the current layer in the ionosphere, for example, \(X = x/h\), and \(X_1 = x_1/h\).

For numerical calculations, we replace the continuous current distribution with an array of surface line currents located at the equidistant points \(X_k = -d/2 + (k + 1/2)\Delta X\) at altitude \(h\) (Figure 12). As a result, the normalized amplitude of magnetic disturbances, \(H = \pi(1 + \Sigma_P)B_x/\mu_0\Sigma_H E_0\) and \(Z = \pi(1 + \Sigma_P)B_y/\mu_0\Sigma_H E_0\), can be calculated from the discrete sums analogous to the above integral relationships (equation (2))

\[
H = -\sum_k A(X_k)E[t - \tau(X_k)] \Delta X,
\]

\[
Z = -\frac{\sum_k (X - X_k)A(X_k)E[t - \tau(X_k)]}{\Delta X} \Delta X.
\]

where \(A(X) = 1 \text{ for } |X| < 1/2, \text{ and } A(X) = 0 \text{ for } |X| > 1/2. \) We adopt the quasiperiodic function with period \(T\) as a model of the incident signal:

\[
F(t) = \frac{\alpha_0 t / T}{1 + \alpha_0 t / T} \times \eta(t) \sin(2\pi t / T) \times \left\{1 + \exp[-\alpha_1(t - t_1)/T]\right\} \left\{1 + \exp[\alpha_2(t - t_2)/T]\right\},
\]

Figure 13. Model signal constructed so as to resemble observed \(P_{DPY6}\) pulsations. Time is normalized to period \(T\).
where \( \eta(t) \) is the Heaviside function. In all subsequent calculations the following set of parameters have been chosen: \( \alpha_0 = 20, \alpha_1 = 30, \alpha_2 = 5, t_1 = 0.1T, \) and \( t_2 = 2T, \) to produce a modeling signal \( F(t) \) resembling the observed \( P_{D\alpha} \) pulsations (Figure 13).

To model a poleward propagation of the wave current along the ionosphere with a particular apparent velocity, we assume that the line current at the point \( x_1 \) is turned on at the moment \( t_1 = \tau(x_1) \), then after elapsed time \( t_2 = \tau(x_2) - \tau(x_1) \) at the point \( x_2 \), and so on (Figure 12). Further on, we assume that the propagation velocity \( V \) along the ionosphere is constant.

We first consider a single, infinitely thin current moving with velocity \( V \) along the ionosphere. This simple notion is often used to model poleward progressing disturbances. The ground signal waveform produced by the corresponding model current, \( J(t) = I(t) \delta(x-Vt) \), is determined by the dimensionless parameter \( U \). It equals the ratio between the timescale \( T/2\pi \) of variations \( I(t) \) and the parameter \( \tau_V = h/V \); that is \( U = T/\tau_V \). As we will see, the parameter \( \tau_V \) determines a limiting time for the observation of the disturbance response at a particular point on the ground from a moving linear current, which is about several \( \tau_V \). The introduction of these parameters, \( U \) and \( \tau_V \), enables one to apply the calculation results for interpretation of observations with different sets of observed parameters.

For the situation when \( U \gg 2\pi \) the results of calculations at different distances from the strip is shown in Figures 14b and 14d for the \( H \) and \( Z \) components, respectively. Here the time is normalized to the period \( T \). The parameters chosen are \( h=100 \) km, \( T=2800 \) s, and \( V=1 \) km/s, so that \( \tau_V = 100 \) s and \( U = 28 \). To give the ionospheric current the opportunity to rise to noticeable magnitude above the selected points at distances from 0 to \( 3 \) km, the moment of the modeling signal onset is chosen to be \( t/T = -0.2 \). In this case, the magnetic signal observed on the ground must have the waveform of a singular spike with semidwidth about \( 2\tau_V \approx 200 \) s only. The disturbance of the \( H \) component is to be observed as a single unipolar excursion, whereas the \( Z \) component is an impulse with fast decaying oscillations. The time delay between spaced stations
corresponds to the propagation velocity $V$ in the ionosphere. The predicted waveform produced by a moving line current obviously does not match our observations.

A slightly better agreement between this model and our observations can be obtained for the set of signal parameters corresponding to $U \leq 2\pi$ and larger values of ratio $\tau_V / T$. The ground signal shown in Figure 14a,c was calculated for $U = 2.8$ and $\tau_V = 10^3$ s. This signal resembles better the observed $P_{DPY}$ features. However, in order to keep the same $T$, the propagation velocity must be only $V = 0.1$ km/s, which is an order of magnitude less than that observed.

Another extreme case, when current variations throughout the strip are coherent ($U = \infty$), corresponds to a magnetostatic field distribution produced by the strip current (not shown). Phase variations are not significant, and the disturbance has unipolar (for the $H$ component) and bipolar (for the $Z$ component) distributions along the ground. Outside the center of the strip the oscillation of the $Z$ component must be out of phase ($\pi$ phase shift). This case also does not fit our observations, which indicate the occurrence of noticeable phase shifts between $H$ and $Z$ components.

Now we present the modeling results accounting for an apparent poleward propagation in the ionosphere with the phase velocity $V = (dr/dz)^{-1}$. The waveforms of possible spatial/temporal distributions on the ground produced by this simple model are surprisingly large. Two dimensionless parameters determine a variety of possible waveforms in the ground signal. The first parameter, $D$, is the dimensionless width of the strip with the ionospheric Hall current, that is $D = d/h$. The second parameter, $U$, corresponds to that already used in the model of a single moving current: it is the ratio between the apparent wavelength of the disturbance in the ionosphere and the strip width, that is $U = VT/d$. According to our observations, typical values of parameters of our model are as follows: the region occupied by the currents is several hundred kilometers wide; quasiperiods $T \simeq 10-50$ min; and the progressing velocity at the ground $V^{(g)} \simeq 0.5-2$ km/s. These, if we assume that $V \simeq V^{(g)}$, the parameters introduced may vary in the intervals $D \sim 3-10$ and $U \sim 3-60$. The case $U \ll 2\pi$ practically never occurs in observations and will not be considered.

As an example of the more typical situation, when $U \geq 2\pi$, we consider the case with $d = 700$ km, $V = 1$ km/s, and $T = 2800$ s, when the parameters are $D = 7$ and $U = 28$. The time evolution of the $H$ and $Z$ components of the disturbance at ground stations located at various distances from the center of the current strip is shown in callout Figure 15. Typical features of the calculated ground structure of the $H$ component (Figure 15, top) are the following: (1) The phase front moves poleward along the ground with an apparent velocity $V^{(g)}$, which varies along the meridian and may differ from the apparent velocity in the ionosphere, $V$. In this example, $V^{(g)} \simeq 0.5V$ beneath the strip; (2) The amplitude of the $H$ component achieves maximal values beneath the current strip, for example, at $x = 0$ and $x = 1.75h$; (3) Outside the strip ($x = 5.5h$ and $x = 7.0h$) the magnitude of the $H$ component decreases rapidly, as $x^{-2}$; (4) The phase delays of the $H$ component are negligible beyond the strip limits (e.g., compare the curves for $x = 3.5h$, $5.5h$, and $7.0h$).

Characteristics of the ground structure of the vertical $Z$ component (Figure 15, bottom) are the following: (1) The amplitude maximizes at points $x \simeq \pm d/2$ ($x = \pm 3.5h$); (2) Beneath the strip the amplitude decreases ($x = 0, \pm 1.75h$) but does not go to zero; (3) Beyond the strip ($|x| > 3.5h$) the magnitude of the $Z$ component decreases more slowly, $\propto x^{-1}$, than does the $H$ component; (4) The phase shift varies along the meridian: it is insignificant beyond the strip limits, and it might be substantial but unsteady beneath the strip, in the region of smallest amplitudes (compare $x = 0$ and $x = 1.75h$). (5) Though because of lack of space the plots are not shown for $x < 0$, we note, however, that the $Z$ components of disturbances in symmetrical points around $x = 0$ are nearly out of phase; that is, the phase shift between them is about $\pi$.

The “point-by-point” comparisons of theoretical predictions with the observations show strikingly good agreement between our simple model and $P_{DPY}$ features. It should be noted that this model is an extreme case of a realistic situation, when not only phase progression but, as well, poleward movement of the ionospheric current region as a whole may take place.

The model predicts that, in general, an apparent propagation velocity, as deduced from the ground magnetic observations, is lower than the actual propagation velocity in the ionosphere (in this example, by nearly a factor of 2). Therefore, if the field-aligned currents are accompanied by particle precipitation into the ionosphere, it might be expected that velocities measured from the magnetometer observations and from auroral images or riometers are different.

8. Conclusions

Quasiperiodic variations of the IMF $B_y$ component with periods of several tens of minutes drive $P_{DPY}$ pulsations in the cusp region under the precondition of southward $B_z$. Most probably, the coupling between the IMF $B_y$ variations and the ground geomagnetic variations at the cusp/cleft latitudes is maintained by field-aligned currents flowing along reconnected interplanetary and geomagnetic field lines. The upper possible frequencies of $P_{DPY}$ pulsations are limited by the cutoff frequency of the effective transfer function of the IMF/magnetosphere coupling. In short, $P_{DPY}$ pulsations are the result of the modulation of the high-latitude current system, reconnected with the solar wind under favorable IMF orientation, by largescale, long-period Alfvén structure in the solar wind.

The quasi-static model of poleward progressing Hall current should be augmented by phase patterns arising from the difference in Alfvén transit times at different latitudes. The theoretical model developed here shows strikingly good agreement with the observed $P_{DPY}$
features. Similar ideas might be helpful in interpretation of the propagation features and polarization structures of other types of dayside transient disturbances (for example, traveling convection vortices).

Acknowledgments. This research was supported by U.S. National Science Foundation (NSF) grant ATM9610072 to Augsburg College and by a supplement from the NSF’s Division of International Programs. V.O.P. acknowledges partial support from the NSF awards OPP-9614175, OPP-9614179, and ATM-9628706. The authors thank K. Yumoto for supplying 210 MM data, and W. J. Hughes and D. L. Murr for supplying CANOPUS magnetometer data. The CANOPUS instrument array was constructed and is maintained and operated by the Canadian Space Agency. The Wind data (PI R. Lepping) are obtained through the NASA/GSFC Web site (http://lep65.gsfc.nasa.gov/nfi/windnfi.html). The useful comments of both referees are appreciated.

Michel Blanc thanks Per Even Sandholt and Tim Yeoman for their assistance in evaluating this paper.

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(Received December 12, 1999; revised April 14, 2000; accepted May 9, 2000.)