Phase skipping and Poynting flux of continuous pulsations

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Abstract

It is recognized that the continuous pulsations (Pc) in the magnetosphere are in general composed of many wave packets and that these wave packets are separated by phase skips. Previous observations by multiple spacecraft and ground magnetometer stations suggest that the phase skipping and packet structure of pulsation signals are most likely due to impulsive wave sources or the beating of waves. However, the magnetic field data alone have not led to an understanding of the propagation of these wave bursts. By using both the electric field and magnetic field data of the ISEE-1 spacecraft, we find that the Poynting flux of Pc 3-4 pulsations in the outer magnetosphere has an impulsive nature. The direction of time-average Poynting flux changes every several wave cycles, and the phase skips in wave signals, both in the magnetic field and electric field, are often found between two adjacent Poynting flux bursts. Furthermore, the phase difference between the electric wave and the magnetic wave indicates that Pc 3,4 waves are generally not in exact resonance, counter to the traditional field line resonance paradigm. These observational results provide us with strong evidence that the “continuous” pulsations in the Pc 3,4 band are in fact maintained by a series of pulses and the phase skips in the wave signals are its natural consequence. The direction of wave energy propagation and its implications are also discussed.
1. Introduction

Magnetic pulsations are one of the most important phenomena in magnetospheric physics. Since Dungey [1954] envisaged that the long but regular periods of magnetic field oscillations (continuous pulsations, or Pc) might be the result of standing waves being excited on geomagnetic field lines, it is generally believed that most Pc 3-5 waves are field line resonances [Chen and Hasegawa, 1974; Southwood, 1974]. Wave activity in the foreshock region has been found to be a major energy source for Pc 3, 4 waves [Troitskaya et al., 1971]. Such a source provides a broad frequency band of energy which can excite multiple harmonics of field lines in the magnetosphere [Takahashi et al., 1984]. However, after many years of pulsation research, what we still eagerly seek from observations is a clear picture of how the pulsation energy propagates in the magnetosphere, since knowledge of this energy path should provide important constraints on and implications for the generation of the wave and the subsequent dynamics of the magnetosphere they cause.

In the following, we first discuss the phenomenon of “phase skipping” in pulsation signals that, as we shall see later, is related to the energy pathway in the magnetosphere. Historically this phenomenon provided the first evidence for the dynamics of Pc 3, 4 paths. It will also lead naturally into the discussion of the physical process of importance, namely the Poynting flux.

Phase skips are sudden changes in the phase of wave signals, while the frequency remains nearly constant. They are a common feature of the continuous pulsations in the magnetosphere. Herron [1966] was perhaps the first to report that continuous pulsations consist of a succession of groups of oscillations, whose frequency remains relatively constant from group to group, but whose phase shifts from zero to almost one cycle from one group to the next.

Despite its long history, the topic of phase skipping is not often treated in the pulsation literature. One of the reasons for its omission is probably that such behavior is not well suited for analysis by conventional Fourier techniques. In addition, for the calculation of phase shifts, simplified models of wave signals that might not be realistic for pulsations are usually assumed a priori to avoid complicated fitting procedures of phase estimation.

An impulsive source of the wave energy and the phenomenon of wave beating are the two major reasons suggested in early work on the phase skipping phenomenon. Mier-Jedrzejowicz and Hughes [1980] studied the pulsations observed simultaneously by multiple spacecraft, and also some events recorded by an array of ground magnetometers. They concluded that the impulsive nature of the energy source is the most likely reason for phase skipping. Lanzerotti et al. [1981] discussed phase shifts when studying the polarization of pulsations at low latitudes. They found that the phase shifts seldom occur simultaneously at all latitudes and therefore concluded that the impulsive process suggested by Mier-Jedrzejowicz and Hughes [1980] is not likely responsible for their observations. Later in this study we will discuss a possible reason that leads to these seemingly contradictory results.

For other contributions to this topic, Ansari and Fraser [1987] studied Pc 3 pulsations observed by low-latitude stations but they could not find any obvious pattern of phase jump occurrences between stations. Ostwald et al. [1993] concluded that a typical pulsation signal exhibits packet structure and phase skipping mainly due to the superposition of interfering waves, although some phase skips that were observed simultaneously at spaced stations are most likely associated with global magnetospheric impulses. McDiarmid and Ziesolleck [1996] devised a model of two overlapping responses that can be either two beating waves or a sequence of impulses. They applied their model to a real pulsation event and found that the result was consistent with the assumption of multiple impulsive excitations.

In addition to the impulsive source and wave beating, the rapid movement of a resonant region relative to the point of observation has also been postulated as a possible cause of phase skipping. However, it was found that the motion of the resonant region would be unrealistically fast [Mier-Jedrzejowicz and Hughes, 1980].

The phase skipping phenomenon is closely related to the Poynting flux of pulsations. Let \( \mathbf{dE} \) and \( \mathbf{dB} \) be the electric waves and magnetic waves, respectively. If we consider a simple condition that \( \mathbf{dE} \perp \mathbf{dB} \), not only does the Poynting vector depend on the amplitudes of \( \mathbf{dE} \) and \( \mathbf{dB} \), it is also a function of the relative phase between \( \mathbf{dE} \) and \( \mathbf{dB} \). When an impulse of new wave energy comes into the system, if it has a different relative phase or a different propagation direction from that of the pre-existing wave, the phase must change in some components of \( \mathbf{dE} \) or \( \mathbf{dB} \). Therefore, it is critical to examine jointly these two properties of pulsations.
For the observation of the Poynting flux of pulsations, Cummings et al. [1978] studied one Pc 4 pulsation event observed by the ATS 6 spacecraft and found that the drift-aligned portion of the Poynting vector suggested a westward propagating wave. Junginger et al. [1985] performed a statistical study of the Poynting vectors for the Pc 5 pulsations observed by the geosynchronous satellite GEOS 2. Although the behavior of the Poynting vectors for the 150-300 second waves was not clear, the perpendicular component of the Poynting vectors associated with 400-600 second waves was directed inward and toward the local noon, which is consistent with the simulation study by Junginger [1985] for the standing shear Alfvén waves driven by the surface waves on the outer boundaries of the magnetosphere. Cahill et al. [1986] studied the azimuthal magnetic oscillations and their corresponding electric waves in the DE-1 data. By comparing the E and B amplitudes and the phase relations between E and B waves, they concluded that their events are consistent with the standing wave model. Takahashi et al. [1994] reported a compressional Pc 3 event observed by the GEOTAIL satellite when it was located in the prenoon sector of the dayside magnetosphere. The calculation of the Poynting flux indicated that the wave energy flowed Earthward, which supports the upstream-wave generation model for Pc 3 pulsations Troitskaya et al., 1986. In this study, we will also discuss the propagation and possible generation mechanisms of Pc 3-4 pulsations implied by the Poynting flux observations.

2. Instrumentation and Data

Both the ISEE 1 electric field and magnetic field data are examined for studying phase skips and the Poynting flux of magnetospheric pulsations. The magnetic fields are measured by the fluxgate magnetometer [Russell, 1978]. The instrument has two commandable ranges, ±8192 nT and ±256 nT. At 16-bit digitization these ranges give 1/4 nT and 1/128 nT resolution.

The electric fields are measured by the spherical double probe experiment [Mozer et al., 1978]. Measurements are made of the potential difference between a pair of 8-cm diameter vitreous carbon spheres. The instrument measures the component of the electric field 8 times per second along the boom direction in the spin plane, which is very close to the ecliptic plane. In the spacecraft coordinate system, the components of DC electric fields in the sunward (x) direction and the dawn-to-dusk direction (y) can be determined by least squares fitting of the data over one spin period 3 seconds. The magnetic fields used in this study also have a time resolution of 3 seconds.

In general, the electric fields in the magnetosphere can be determined by the precision with an uncertainty less than 1.0 mV/m under average conditions, and the electric field in the dawn-to-dusk direction, \( E_y \), can be measured with somewhat better accuracy than 0.5 mV/m because the symmetry between two probes is better in this direction [Cattell et al., 1986]. However, for pulsation events, the errors are expected to be much smaller since the wave signatures can well be described without the exact knowledge of nearly constant offsets [Pedersen et al., 1984].

The pulsations events analyzed are selected when the waves of the same frequency can be seen in both electric-field and magnetic-field data. Figure 1 shows an example of Pc 3-4 waves observed by the ISEE-1 spacecraft on November 24 (Day 328), 1977 when the spacecraft was located approximately at \((8.5, -4.5, 3.9) R_E \) in GSM coordinates. The short data gaps are caused by the sounder experiment onboard the spacecraft [Harvey et al., 1978], which interfered with the electric field experiment. The average wave frequency for this event is 24 mHz. Another Pc 3-4 example observed on November 3 (Day 307), 1977 when ISEE 1 was located at \((9.3, 1.0, 4.1) R_E \) is shown in Figure 2, where the solid lines are the linearly detrended values and the dashed lines are the bandpass filtered values over the frequency range 20-35 mHz. The Hanning window is applied to the filter in order to reduce the ringing effect. The data gaps are first treated by an interpolation, and the data in the interpolated region are removed after the filtering process. It can be seen that, for both the electric field and magnetic field data, the filter preserves the phase of the original wave signals. In addition, the similarity of the amplitude envelope of these two independently measured signals \((E_x, B_y)\) attests to the reality of the signal as a natural phenomenon.

The full 3-D electric field vectors are required to perform the Poynting flux calculation. Having two components of the electric field and three components of the magnetic field, we may calculate the electric field along the direction of spacecraft’s spin axis (z) by assuming that the MHD condition \( \mathbf{E} \cdot \mathbf{B} = 0 \) is conserved, i.e., \( E_z = -(E_x B_z + E_y B_y)/B_z \). Since this calculation may produce large errors when \( B_z \) is comparatively small, we adopt the criterion suggested by Pedersen et al. [1984] that the full 3-D electric field
vectors are calculated only when the angle between $\mathbf{B}$ and $\mathbf{z}$ is less than $80^\circ$.

3. Observations

The knowledge of the phase of wave signals is essential in this study. In order to calculate the instantaneous phase of the wave signals and the Poynting flux, the data are first band-passed filtered as described in the previous Section. The instantaneous phase is estimated by the least squares fitting of a sinusoid [Bloomfield, 1976]. For each estimate of phase, the length of the sinusoid fitted to the data is one wave cycle. For the event on Day 307, 1977, the phase of the signals relative to that of the sinusoid is plotted in Figure 3, where the results for $E_x, E_y, B_x,$ and $B_y$ in spacecraft coordinates are shown. Because the reference sinusoid has a constant frequency, the phase of the signals usually appears to be gradually drifting due to slight frequency differences with the observed waves. Nevertheless rapid changes in phase can still be found frequently. The arrows in Figure 3 represent the phase skips that are comparatively clear. Although the phase skipping phenomenon in pulsations has been seen in the magnetic field data both in space and on the ground, Figure 3 presents the first time that the phase skips of pulsations are demonstrated in both the electric field and magnetic field data in space. It can also been seen from the Figure that most phase skips seen by one instrument have corresponding phase skips seen by the other instrument. Since the two instruments perform independent measurements, this suggests that the phase skips are caused by some physical process in space rather than some instrumental artifact. It should be mentioned that the sinusoid fitting method and the filtered signals produce a smoother shift in phase even though the reality could have a sharp phase skip. The time when phase skips occur may also have some uncertainty of the order of one wave cycle. This is an intrinsic problem that also applies to other published techniques for phase skip identification.

In the following, all the vectors will be expressed in the field-aligned coordinates, which are defined as $\mathbf{b} = \mathbf{B}/|\mathbf{B}|$ (field-aligned), $\mathbf{e} = \mathbf{b} \times \mathbf{r}/|\mathbf{b} \times \mathbf{r}|$ (eastward), and $\mathbf{n} = \mathbf{e} \times \mathbf{b}$ (outward), where $\mathbf{r}$ is in the radial direction. A schematic diagram of this field-aligned coordinate system is shown in Figure 4a.

The Poynting flux $\mathbf{S}$ can be calculated in a straightforward way by having the full 3-D vectors of electric fields and magnetic fields. The top three panels of Figure 5 show the Poynting vectors in the field-aligned coordinates for the Pc 3-4 event on Day 328, 1977. The Poynting vectors oscillated at the rate twice of the wave frequency and they appeared to have a bursty nature. From the viewpoint of energy propagation it is customary to use the time-average value of the Poynting flux, which is sometimes called the wave intensity in optics. If the perturbations in the electric field and magnetic field are $d\mathbf{E}$ and $d\mathbf{B}$, respectively, the time-average Poynting flux $\langle \mathbf{S} \rangle$ is

$$\langle \mathbf{S} \rangle = \frac{1}{T} \int_0^T \mathbf{S} dt = \frac{1}{T} \int_0^T \frac{d\mathbf{E} \times d\mathbf{B}}{\mu_0}$$ (1)

where $T$ is the wave period. The magnitude and orientation of the time-average Poynting vector $\langle \mathbf{S} \rangle$ and the magnetic perturbations for the same event (Day 328, 1977) are plotted in the middle three panels of Figure 5. The orientation of the Poynting flux is represented by the two angles $\alpha$ and $\beta$, whose definitions are shown in Figure 4b. When $\alpha = 0^\circ$, the Poynting flux $\langle \mathbf{S} \rangle$ is field-aligned; when $\alpha = 90^\circ$, $\langle \mathbf{S} \rangle$ is perpendicular to the field. The direction of the perpendicular component of $\langle \mathbf{S} \rangle$ is defined by the angle $\beta$. The rapid modulation of $|\langle \mathbf{S} \rangle|$ indicates us again that the energy of the Pc 3-4 waves flows in a bursty fashion, and the direction of $\langle \mathbf{S} \rangle$ changes after several wave cycles. The magnetic perturbations in the field-aligned coordinates are plotted in the bottom three panels. When the change of Poynting flux direction is examined in detail, we find that the phase skips in the wave signals occur when the Poynting flux rapidly changes its direction. For example, at 20:57 UT, the Poynting flux $\langle \mathbf{S} \rangle$ rapidly rotated from the direction antiparallel to the field to the direction toward the field. A phase skip in $dB_0$ is found at the same time. More examples are indicated in the Figure. Here we see the directional change of Poynting vectors and the phase skips have a one-to-one relation.

Figure 6 shows the simultaneous and time-average Poynting vectors $\langle \mathbf{S} \rangle$ and $\langle \mathbf{S} \rangle$, respectively) for the Pc 3-4 event on Day 307, 1977. Again the Poynting flux changes its directions every several wave cycles. The phase skips also occurred when the Poynting flux changed its direction.

As seen in Figures 5 and 6, Poynting vectors can be in many directions. In order to understand the statistical features of Poynting flux directions, 29 clear Pc 3-4 events observed by ISEE-1 have been examined. Table 1 lists those events and the corresponding interplanetary magnetic field (IMF) conditions observed by either the IMP 8 or the ISEE 3 spacecraft. The
ISEE 3 spacecraft was generally located close to the sunward libration point at \( \approx 200 R_E \) upstream of the Earth, and the IMP 8 spacecraft orbits the Earth with an apogee \( \approx 40 R_E \). The delay of the solar wind travel time from the spacecraft to the magnetopause is considered. In the 23 events that the IMF data are available, 16 of them occurred when the IMF cone angle \( \cos^{-1}(B_x/B_t) \leq 45^\circ \), and none occurred when the IMF cone angle was greater than \( 60^\circ \). This is consistent with the scenario that the upstream of the bow shock provides an important energy source for Pc 3,4 waves [Troitskaya et al., 1971]. In addition, only 6 of the 23 events occurred under southward IMF conditions, which suggests that the reconnection process on the dayside magnetopause is not an important energy provider for these wave activities.

The Poynting vectors of the energy impulses are studied statistically to understand the propagation of wave energy. The samples are selected when the magnitude of the time-average Poynting flux is at its maximum, e.g., the peak of \( |\mathbf{S}| \) at 20:58 UT in Figure 5. Totally 194 Poynting flux samples are obtained from the events listed in Table 1. Figure 7 shows the distribution of their orientations in terms of the \( \alpha \) and \( \beta \) angles. The occurrence rates of the \( \alpha \) and \( \beta \) angles of the Poynting flux are also shown alongside the \( \alpha-\beta \) plot. It can be seen that most of the Poynting vectors are oriented in the direction close to the ambient magnetic field. Approximately 73% of the vectors have an \( \alpha \) angle less than \( 45^\circ \) (or larger than \( 135^\circ \)). In addition, the perpendicular component of \( \mathbf{S} \) is more likely to be close to the east-west direction. The Poynting vectors with outward energy flow \( (|\beta| < 90^\circ) \) slightly outnumber those with inward energy flow \( (|\beta| > 90^\circ) \).

Poynting vectors in the n-e plane, which is perpendicular to the background magnetic field, and their locations of measurements are plotted in Figure 8 for further visualizing the energy propagation in the magnetosphere. Figure 8a shows the perpendicular component of \( \mathbf{S} \), or \( (\mathbf{S})_\perp \), of the 194 Poynting flux samples as in Figure 7. The length of the arrows is proportional to the logarithm of \( |\mathbf{S}| \). The arrows form into subgroups in the Figure since each wave event has several Poynting flux samples due to multiple impulses of wave energy. It is apparent that the directions of \( (\mathbf{S})_\perp \) may vary dramatically in a relatively small region in the magnetosphere as seen previously in Figures 5 and 6. In contrast to Figure 8a, Figure 8b shows the mean Poynting vectors for the 29 Pc 3-4 events. In the morning sector, the wave energy appears to flow inward and from dawn to noon. In the afternoon sector, most of the wave energy still propagates eastward although the picture is less clear. Overall, we find that the mean Poynting flux in the n-e plane flows eastward and inward. However, each event contains several impulses of wave energy which may have very different directions of propagation.

4. Discussion

In this study it is found that the phase skipping phenomenon in pulsation signals is directly related to the directional change of the Poynting flux. This is not an unexpected result since the Poynting flux is a function of the relative phase of the magnetic and electric oscillations and phase skips are due to changes of phase relative to the reference signal. Although these two properties do not have an absolute relationship, it is very likely that phase skips in either \( dE \) or \( dB \), or both, will be observed when a series of wave energy impulses with different propagating directions come into the system.

When discussing the impulsive wave energy that seems to be consistent with our observations, it is important to assess how field-line and cavity-like resonances play a role in this picture. There is observational evidence of field-line resonances in the magnetosphere [e.g., Greenwald and Walker, 1980; Takahashi et al., 1984; Engebretson et al., 1986; 1987]. Mier-Jedrzejowicz and Hughes [1980] conjecture that an impulse initiates the wave packets in phase at all stations, and then the local field lines act as resonators in which the signals drift out of phase due to the slight differences in magnetic field geometry or particle populations at the different field lines. A new impulse brings the signals back in phase again. In this picture the impulse and the resonance should have comparable importance in terms of wave energy.

First we may obtain some information from the simultaneous Poynting vectors \( \mathbf{S} \) as shown in Figures 5 and 6. If we consider a transverse wave causing field line oscillations, the Poynting vectors behave very differently depending on whether the wave is traveling or standing. Figure 9 is a diagram of the Poynting vectors for the two different schemes. Even though the wave amplitudes for both conditions are set to be the same and the magnitude of Poynting vector oscillations is consequently the same, the traveling wave propagates energy, while the standing wave produces no net energy flux. The Poynting vectors in Figures 5 and 6 more resemble the traveling-wave pattern.
Thus, for the Pc 3-4 wave activities in our observations the traveling-wave component is stronger. We may also estimate the resonant condition by examining the phase difference between $dE$ and $dB$ [e.g., Singer et al., 1982]. If the phase difference is 90°, the wave is standing and a resonant condition is reached. Figure 10 compares the orthogonal components of $dE$ and $dB$ for the Pc 3-4 event on Day 328, 1977. The phase difference is a strong function of time and it suggests that the spacecraft was not observing a fine standing wave structure.

A Pc 5 event is also studied here for comparison. The ISEE-1 spacecraft observed a 4-mHz wave event both in the electric field and magnetic field (Figure 11) when the spacecraft was located at $(1.5, -5.8, 4) R_E$ in GSM coordinates. The wave forms are clearly seen in the raw data. The waves are mainly in the transverse components and they are linearly polarized (not shown). Figure 12 shows the phase comparison between $dE$ and $dB$ for this event. It is clear that the spacecraft was seeing a standing wave and the structure persisted for approximately 45 minutes. This Pc 5 event has a very different appearance from the two Pc 3-4 events presented and it suggests that the two classes of pulsations have different nature.

While many studies have shown evidence of Pc 3-4 field line resonances in spacecraft observations [e.g., Takahashi et al., 1984; Cahill et al., 1986; Engebretson et al., 1986; 1987], the observations in this study present a different result. It is possible that the inconsistency arises because the locations of observations are different. In this study, the observations were mainly made in the region outside the geosynchronous orbit where the fundamental model frequency is likely in the Pc 5 band. However, this outer part of the magnetosphere contains strong broadband Pc 3-4 waves that are strongly influenced by the foreshock’s upstream waves. The Pc 3-4 events presented by Cahill et al. [1986] are observed at lower $L$ shells ($L = 2.5 - 5.7$), where the fundamental mode frequency shifts to a higher value in the Pc 3-4 band. Therefore, the impulsive nature of the Pc 3-4 in the outer magnetosphere found by this study does not necessarily conflict with the early works which find the resonant behavior of Pc 3-4 at inner $L$-shells.

In Figure 7 we see that most of the time-average Poynting vectors, or equivalently the energy flow of the pulsations, have a strong field-aligned component. If an Alfvén wave is traveling along the field line toward the ionosphere, the high conductivity in the dayside ionosphere will result in a reflected wave traveling back into the magnetosphere.

The Alfvénic travel time is calculated in Appendix. For the Pc 3-4 event on Day 328, 1977 as seen in Figure 5, the ISEE-1 spacecraft was located at $(8.5, -4.5, 3.9) R_E$ in GSM coordinates, or $r = 10.4 R_E$, $\theta$ (latitude) = 7.3°, $\phi$ (longitude) = −25.9° in SM coordinates equivalently. Although ISEE-1 density data are not available for this event, the Fast Plasma Experiment (FPE) [Bame et al., 1978] on ISEE-2 recorded the ion charge density of approximately 0.5 cm$^{-3}$. At that time ISEE-1 was following the ISEE-2 trajectory and only behind by 4 minutes, and therefore we may take this density as what would have been observed by ISEE-1 since the two spacecraft were very close to each other. Substituting the density and spacecraft locations into Equation (A6) (assuming $m = 3$), we obtain that $\tau_N = 63$ sec and $\tau_S = 258$ sec. In Figure 5, the time for the field-aligned component of the Poynting vector changing from minimum (negative) to maximum (positive) is about 3 min (e.g., from 20:56 UT to 20:59 UT; from 21:05 UT to 21:08 UT). This time is comparable to the calculated $\tau_S$ value, which represents the time for an Alfvén wave to travel from the spacecraft location following the field line to the southern ionosphere and then travel back through the same path. It should be noted that the above calculation is only a rough estimate since the density model and magnetic field model may be simplistic, and the density of heavy ions has not been included in the calculation. However, it is suggestive that one wave packet could produce multiple phase skips in the wave signals by being reflected from the ionosphere.

Of course one cannot totally ignore the role of wave beating in interpreting phase skipping. Even when a strong impulse of wave energy comes into the system, there must be a certain amount of interference between the incoming wave and the pre-existing wave. However, it can be seen in Figure 5 that the wave energy can come from many different directions within 50 minutes (or 25 minutes for Figure 6). Therefore the phase skipping phenomenon must be more complicated than the beating of two sinusoidal waves.

From Figures 5 and 6 it can be seen that the phase skipping phenomenon, or the impulses of wave energy, occurred approximately every 5-10 minutes. One might speculate that these energy impulses are associated with the flux transfer events (FTEs) on the dayside magnetopause since the average time interval between FTE signatures is about 8 minutes [e.g., Lockwood and Wild, 1993; Kuo et al., 1995]. First
of all, as we have described previously, one Alfvénic wave packet could produce multiple phase skips and therefore it is difficult to compare the recurrence of FTEs with the separation time of two phase skips. Secondly, the statistical result of Berchem and Russell [1984] indicates that FTEs occur almost exclusively during southward IMF conditions, while Table 1 shows that only 6 out of 23 events occurred during the time when the IMF was southward. In addition, Kawano and Russell [1996] also show that statistically the occurrence of FTEs is not associated with the foreshock geometry, which is important in controlling the Pc 3, 4 activities in the magnetosphere [e.g., Russell et al., 1983].

Our results could also address some apparent inconsistencies in the early work on this topic. Lanzerotti et al. [1981] and Ansari and Fraser [1987] studied the phase skips of low-latitude (L \( \simeq 1.9 \) for the former study and \( L \simeq 1.8 - 2.7 \) for the latter one) pulsations measured by ground magnetometer arrays. Both studies found that the phase skips seldom occur simultaneously at all latitudes and they concluded that the impulsive process suggested by Mier-Jedrzejowicz and Hughes [1980] could generally not be responsible for their observations. Since few Poynting vectors in our observations (see Figure 7) are perpendicular to the \( L \)-shells, i.e., \( \alpha \approx 90^\circ \) and \( \beta \approx \pm 180^\circ \), it is possible that only a few examples of globally impulsive events would be found in multi-station observations. However, the source of wave energy can still be considered impulsive. A caveat of this argument is that our study is based on the spacecraft observations at high \( L \)-shells whereas the aforementioned studies made their observations at low \( L \)-shells.

Our statistical result of Poynting flux directions shows that most of the Poynting vectors for Pc 3-4 pulsations are approximately tangential to the \( L \)-shells, i.e., they are mainly field-aligned or in the azimuthal direction. A small portion of Poynting vectors do show a strong component perpendicular to \( L \)-shells (Figure 7). The simulation work of Junginger [1985] shows that near the resonant region a strong field-aligned Poynting flux flowing toward the closer ionosphere due to the finite ionospheric conductivities. However, Junginger’s results cannot be applied to our observations here since he discusses a steady process opposed to the impulsive nature of the field-aligned Poynting flux in our observations, where the orientation of the Poynting flux can change from being parallel to anti-parallel to the ambient field in several minutes (Figures 5 and 6). In addition, our observations of Pc 3, 4 waves show a traveling-wave pattern, whereas Junginger simulated the conditions for field line resonances. It is also not likely that these changes are due to the fast variation of ionospheric conductivities and therefore the separation point (or the “null point” as in Allan [1982]) for the Poynting flux flowing to different ionospheres moves northward and southward rapidly along the field line. Table 2 indicates that when the ISEE 1 spacecraft was located in either the northern or southern hemisphere, the numbers of northward Poynting vectors and southward Poynting vectors are in fact comparable.

Therefore, our observations suggest the importance of the impulsive process and the reflection of Alfvén waves from the ionosphere, rather than the ionospheric dissipation. This is expected for the dayside region where the ionosphere acts as a good reflector for incident Alfvén waves (see, for example, Hughes [1974]). It is also possible that the fast-mode waves may be reflected at some inner boundary, such as the plasmapause, and this reflection may explain some outward propagating Poynting vectors shown in Figure 7. Figure 13 qualitatively sketches the propagation of the Pc 3, 4 wave packets as observed in this study.

We find from the single-spacecraft measurements here that the propagation of Pc 3,4 wave energy is not simply propagating inward from an external energy source. The IMF conditions seem to support the model of the upstream wave source for Pc 3,4 waves, but the propagation pattern is too complicated to be resolved by this study. The sources for outward propagating wave energy also requires further investigations, although it is possible that the ion drift instability may act as the internal generation mechanism [Anderson et al., 1990]. Future work, possibly by multiple spacecraft observations, might provide understanding of these issues.

5. Conclusions

We have examined the Poynting flux and phase skipping properties of the magnetic pulsations. The Poynting flux for Pc 3-4 waves has bursty appearance. This result and the traveling wave-like structure of the Poynting vectors tell us that the Pc 3-4 waves in the outer magnetosphere have an impulsive energy source. However, the waves are continuous in appearance since the bursts of wave energy feed into the magnetosphere repeatedly. This conclusion departs from the traditional paradigm that most of
the pulsations in the magnetosphere are field line resonances, but it should be pointed out that the observations presented in this study are mainly located outside the geosynchronous orbit, which may not represent the situation in the inner magnetosphere. Nevertheless, the wave impulses are capable of traveling across L-shells and they may explain the observations that Pc 3 waves often have the same wave frequency at multiple stations located over a wide range of latitudes with quite different resonant frequencies [e.g., Chi et al., 1994].

We also examined a Pc 5 event which does show a clear field-line-resonance structure, in contrast to the traveling-wave structure for Pc 3-4 waves. It is concluded that, in the outer magnetosphere, the field line resonance is important for some low-frequency pulsations such as Pc 5 waves but it is not a dominant effect for Pc 3-4 activities.

It is also found that the phase skipping phenomenon and the directional change of Poynting flux are related. The energy impulses of pulsations alter the direction of the Poynting flux and also abruptly change the phase of wave signals. This finding helps confirm that the phase skipping phenomenon that has been previously studied in the literature only by its magnetic signatures is present in the electric field also and is caused by the impulsive nature of the energy source. It is possible that one wave impulse could cause multiple phase skips in observations due to the Alfvén component of the wave energy being reflected by the ionosphere.

Appendix: Alfvénic Travel Time in the Magnetosphere

This travel time of an Alfvén wave from one point to another on the same field line is

$$\tau = \int_{s_1}^{s_2} \frac{ds}{v_A} = \int_{s_1}^{s_2} \frac{\mu_0 \rho(s)}{B(s)} ds (A1)$$

In the following calculations, we will adopt the model of a hydrogen plasma with a density distribution varies as

$$\rho = m_p n = m_p n_0 \left( \frac{r}{r_0} \right)^m (A2)$$

where $r_0$ is the geocentric distance to the equatorial crossing point of the field line under consideration, and $n_0$ is the proton number density at $r_0$. Since $r = r_0 \cos^2 \theta$ for a dipole field line, the number density varies along the field line as $n = n_0 \sin^{-2m} \theta$. The background magnetic field varies along the field line as

$$B(r, \theta) = \frac{m u_0 M}{4 \pi r_0^3} \frac{(1 + 3 \sin^2 \theta)^{1/2}}{\cos^6 \theta} (A3)$$

where $M$ is the earth’s magnetic moment $8 \times 10^{22}$ Amp m$^2$.

Consider an Alfvén wave that travels from the spacecraft location following the field line to the ionosphere and travels back through the same path. The latitude at the foot of the field line on the ionosphere is $\theta_N = \cos^{-1} \sqrt{1/L}$ or $\theta_S = -\cos^{-1} \sqrt{1/L}$ depending on the ionosphere of concern. Therefore, the travel time is

$$\tau_N = 2 \int_{SC}^{N,Iono.} \frac{\sqrt{\mu_0 \rho}}{B} ds = 2 \left( \frac{m_p n_0}{\mu_0} \right)^{1/2} 4 \pi r_0^4 \int_{\theta_{SC}}^{\theta_N} \cos^{-m} \theta d\theta = 1.9 \times 10^{-5} n_0^{1/2} L^{1/4} \int_{\theta_{SC}}^{\theta_N} \cos^{-m} \theta d\theta (A4)$$

where $ds = \sqrt{r^2 + (\frac{dr}{d\theta})^2} d\theta$, or

$$\tau_S = 1.9 \times 10^{-5} n_0^{1/2} L^{1/4} \int_{\theta_S}^{\theta_{SC}} \cos^{-m} \theta d\theta (A5)$$

It should be noted that the above calculation can only be considered as a rough estimate of the Alfvénic travel time. First of all, the magnetospheric field at larger L-shells deviates from the dipole model. Another reason, which might be even more serious, is that the power-law density model as used in the calculation is a crude estimation. The $m$ value in the density model can range from 0 to 6 [cf. Cummings et al., 1969]. For $m = 3$, Equation (A4) or (A5) can also be written as

$$\tau = 1.9 \times 10^{-5} n_0^{1/2} L^{1/4} \left[ \frac{3 \theta}{8} + \sin(2\theta) + \sin(4\theta) \right]^{6/2} \int_{\theta_S}^{\theta_N} d\theta (A6)$$

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Table 1. List of Pc 3, 4 Events

<table>
<thead>
<tr>
<th>Event (year, d.o.y.)</th>
<th>Frequency, mHz</th>
<th>IMF $B_T$, nT</th>
<th>IMF $\theta_{BX}$, deg</th>
<th>IMF $B_Z$, nT</th>
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<tr>
<td>1977 307</td>
<td>26</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1977 328a</td>
<td>25</td>
<td>4.6</td>
<td>39</td>
<td>2.6</td>
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<tr>
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<td>24</td>
<td>4.3</td>
<td>47</td>
<td>2.4</td>
</tr>
<tr>
<td>1978 205a</td>
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<td>—</td>
<td>—</td>
</tr>
<tr>
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<td>5.6</td>
<td>51</td>
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<tr>
<td>1978 209</td>
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<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
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<td>1980 352c</td>
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<td>5</td>
<td>0.0</td>
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<tr>
<td>1981 189</td>
<td>34</td>
<td>5.6</td>
<td>34</td>
<td>-1.9</td>
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Table 2. Number of Poynting flux samples in the northern and southern hemispheres and different Poynting flux orientations

<table>
<thead>
<tr>
<th>Spacecraft Location</th>
<th>$0^\circ \leq \alpha &lt; 45^\circ$</th>
<th>$135^\circ &lt; \alpha \leq 180^\circ$</th>
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<tr>
<td>Magnetic Latitude &gt; 0</td>
<td>59</td>
<td>51</td>
</tr>
<tr>
<td>Magnetic Latitude &lt; 0</td>
<td>17</td>
<td>14</td>
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</table>
Figure 1. An example of Pc 3-4 waves observed on November 24 (Day 328), 1977. The measurements are presented in the spacecraft coordinates that $x$ is sunward, $y$ is roughly duskward, and $z$ is along the spin axis.

Figure 2. Another example of Pc 3-4 waves observed on November 3 (Day 307), 1977. The solid lines show the detrended values and the dashed line filtered values. The frequency band for the filter is 20-35 mHz.
Figure 3. The relative phase of the filtered signals to the phase of the modeled sinusoid. The phase skips are indicated by arrows.

Figure 4. (a) Schematic diagram of the field-aligned coordinate system. (b) Angles for representing the orientation of the time-average Poynting flux.
Figure 5. The Poynting vectors in field-aligned coordinates, time-average Poynting flux, and the magnetic perturbations for the Pc 3-4 event on Day 328, 1977.
Figure 6. Same as Figure 5 except for the Pc 3-4 event on Day 307, 1977.
Figure 7. Distribution of the $\alpha$ and $\beta$ angles of 194 time-average Poynting vectors.

Figure 8. (a) The Poynting vectors in the n-e plane and the locations of observations. The length of the arrows is proportional to the logarithm of $|S|$. (b) As (a) except that each arrow represents the mean Poynting vector for an event in Table 1.
Figure 9. The schematic diagrams of the product of $E$ and $B$ for the traveling-wave case and the standing-wave case. $T$ is the wave period.

Figure 10. The phase comparison between $dE$ and $dB$ for the Pc 3-4 event on Day 328, 1977.
Figure 11. The Pc 5 event observed by the ISEE-1 spacecraft on November 3 (Day 307), 1977.

Figure 12. The phase comparison between $dE$ and $dB$ for the Pc 5 event on Day 307, 1977.
Figure 13. Sketch of Pc 3, 4 impulses in the outer part of the magnetosphere.