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Pc1 pearls revisited: Structured electromagnetic ion cyclotron waves on Polar satellite and on ground

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Abstract. We study an event of structured electromagnetic ion cyclotron (EMIC) waves observed by the Polar satellite in good conjunction with the Finnish ground stations on April 25, 1997. Polar observed two EMIC wave bands around the plasmapause. He^+ band waves consisted of repetitive bursts which were observed on ground as a classical Pc1 pearl band. H^+ band waves occurred over a large latitude range of more than 5° invariant latitude and were observed on ground as a broad, diffuse Pc1 pearl band with several subbands. We found the same repetition period of ~100 s for the Polar He^+ band bursts and ground Pc1 pearls, in conflict with the bouncing wave packet (BWP) model. Comparing the burst structure of He^+ band waves in Polar and on ground, we found a transit time of ~45 s and an average group velocity of ~500 km s^{-1}. Within the BWP model this velocity would lead to a pearl repetition period of more than 250 s, in dramatic contradiction with the observed repetition period. Moreover, the bursts of the two Polar bands were roughly simultaneous with no significant dispersion, contrary to the expectation of the BWP model. These results clearly reject the classical BWP model, i.e., that Pc1 pearls are generated by one wave packet bouncing from one hemisphere to another. Instead, we find that EMIC waves were accompanied by long-period ULF waves which had a period very close to the repetition period of the simultaneous EMIC bursts. Interestingly, plasma density showed simultaneous fluctuations with roughly the same period. As an alternative to the BWP model, we discuss models where the EMIC wave packet structure and ULF waves are connected. We note that the suggested relation of EMIC wave packets and ULF waves offers a new explanation to the well-known preference of Pc1 pearls for the plasmapause. We have also estimated the full Poynting flux of EMIC waves for the first time, using the three components of electric and magnetic fields. The magnitude of the total Poynting flux of the He^+ band waves was ~20–25 μW m^{-2} and strongly directed downward away from the equator.

1. Introduction

Pc1 pulsations are electromagnetic ion cyclotron (EMIC) waves in 0.1–5.0 Hz frequency range, generated in the equatorial magnetosphere by protons and heavier ions in energy range of ~10–100 keV [*Brice*, 1965; *Cornwall*, 1965]. Structured Pc1s (also called pearl pulsations) characterized by regular amplitude variations are the most common form of Pc1 pulsations observed typically in the morning sector at low latitudes to mid-latitudes. Repetition period, i.e., the time interval between two successive amplitude maxima, ranges from several tens of seconds to a few minutes. According to bouncing wave packet (BWP) model [*Obayashi*, 1965], the repetitive structure of pearl pulsations is generated by a wave packet bouncing along the field line between opposite hemispheres, losing part of its energy when reflecting from the ionospheres and gaining energy when traversing through the equatorial growth region. In addition to the BWP model, other, alternative models of pearl formation have been suggested. Recently, observations supporting Pc1 wave growth by long-period ULF waves have been presented [*Plyasova-Bakounina*

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et al., 1996; *Mursula et al.*, 1997, 1999, 2000; *Rasinkangas and Mursula*, 1998]. According to this model, the marginally stable plasma [*Gail*, 1990] is periodically set into unstable state by the influence of ULF waves.

Only a few cases of satellite observations of structured EMIC waves have been observed so far. *Erlandson et al.* [1992] observed a band of structured waves by the Viking satellite at $L = 3.6$–4.1 in the prenoon sector, and *Erlandson et al.* [1996] observed one at $L = 5.1$–5.5 in the noon sector. Both studies observed a similar repetition period at Viking and on ground contrary to the BWP model, according to which the burst rate at satellite should be twice that on ground. *Mursula et al.* [1997] observed EMIC wave bursts at $L = 5.6$–6.2 with a repetition period of 40–45 s in relation to a Pc1 chorus event on ground. The burst repetition structure was analyzed in detail, and the BWP model could be excluded as a mechanism producing such burst structure. Instead, simultaneous long-period ULF waves of upstream origin were detected by several satellites and on ground with a frequency closely matching with the EMIC repetition period [*Rasinkangas and Mursula*, 1998].

In this paper we study structured Pc1 pulsations observed on April 25, 1997, simultaneously by the Finnish search-coil magnetometer network and by the electric and magnetic field instruments on board the Polar satellite in a good conjunction. We note that this is the first study of EMIC waves where the complete three-component electric and magnetic fields were available allowing, for example, one to verify the electromagnetic nature of EMIC waves and to determine the full Poynting vector and the mode structure of waves. The first preliminary features of the event, based on electric field observations only, were presented by *Mursula et al.* [1999]. In section 2 we briefly describe the instrumentation used in this study and define the coordinate system of satellite observations. In section 3 we describe the wave observations. Section 4 discusses the latitudinal width and coherence of EMIC waves, and section 5 discusses the effect and properties of ULF waves. In section 6 we derive the transit times and velocities, and in section 7 we present the Poynting flux calculations. Conclusions and final notes are presented in section 8.

2. Observational Setting

The Electric Field Investigation (EFI) instrument [*Harvey et al.*, 1995] consists of two orthogonal pairs of wire booms in the satellite spin plane and one shorter pair of rigid booms parallel to the spin axis. The potential difference of each probe pair is measured to obtain the three components of the electric field vector from DC to over 20 kHz with a dynamic range of 0.02–1000 mV m^{-1}. EFI samples data over the whole orbit at the rate of at least 20 samples s^{-1} in its nominal operation mode. On the basis of its high sensitivity, EFI has proven to be an excellent observatory of EMIC waves [*Mursula et al.*, 1999; *Bräysy and Mursula*, 2001].

Magnetic field observations by the Magnetic Field Experiment (MFE) [*Russell et al.*, 1995] on the Polar spacecraft are used here together with electric field observations. MFE consists of two triaxial fluxgate magnetometer sensors mounted on a 6 m boom. A field-aligned coordinate system is used in this study. Positive z axis (FACz) points in the direction of the Earth's magnetic field vector at the spacecraft location, positive x axis (FACx) lies in the plane of the Earth's magnetic field passing through the spacecraft's location and points toward the Earth, and y axis (FACy) completes the right-handed orthogonal system, pointing roughly westward.

3. Observations

Figure 1 shows the field line projected footpoint of the northward bound track of the Polar satellite on April 25, 1997, crossing the invariant latitudes between ~55° and 65° at 0800–1000 UT in the 1130 magnetic local time (MLT) sector. Throughout this time the Polar footpoint was in a fair conjunction with the Finnish search-coil magnetometer network. Since the satellite crosses L shells very quickly close to its perigee in the Southern Hemisphere at ~0800-0815 UT (see Figure 1), restricting the wave analysis there, we will concentrate on the observations in the Northern Hemisphere and comment on the perigee observations only later.

Polar observed two simultaneous bands of EMIC waves in the Northern Hemisphere at ~0915–0945 UT (geomagnetic latitude (GMLat) 16.5°–30.0°, $L = 4.3$–6.2, 61.1°–66.3° invariant latitude (ILAT), 1130 MLT; see

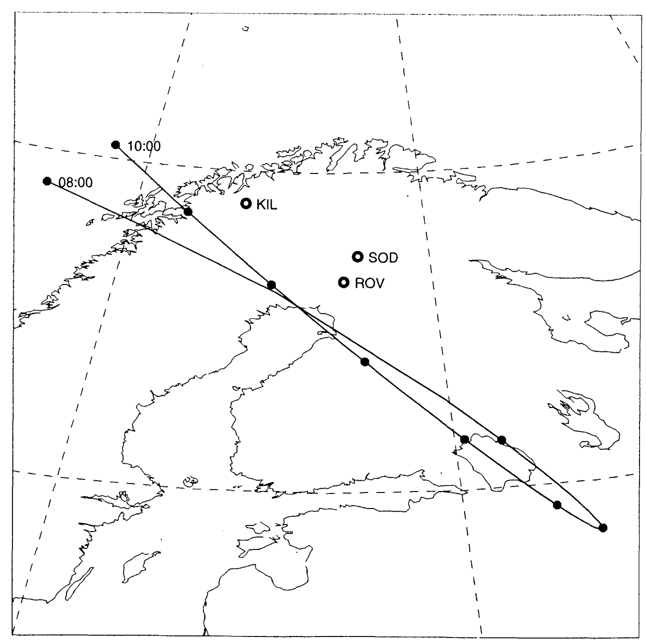

Figure 1. Footprint of the Polar satellite on April 25, 1997, at 0800–1000 UT. Solid circles denote exact quarter-hours. Open circles show the location of the three Finnish search-coil magnetometers.

Plate 1b). The two wave bands are organized by the equatorial helium cyclotron frequency F_{He^+}. The lower band below F_{He^+} (the He^+ band) had a midfrequency of ~1.0–1.2 Hz. The three most intensive bursts of this band occurred at 0918–0923 UT and had a maximum peak-to-peak amplitude of ~3 mV m^{-1}. The repetition period of these bursts was ~90–100 s. The midfrequency of the higher band between F_{He^+} and F_{H^+} (the H^+ band) decreased from 2.4 to 1.4 Hz, following the decreasing value of magnetic field intensity with increasing radial distance. The maximum amplitude of the H^+ band was ~4 mV m^{-1}. The repetition period of the bursts of the H^+ band at the beginning (0915–0925 UT) was very similar to that of the simultaneous He^+ band, and, in fact, the bursts of the two bands were almost simultaneous (see Plate 1b). From 0925 UT onward the burst structure of the H^+ band was irregular, until at the end of the band from ~0940 UT onward, the burst structure was again more regular with a repetition period of ~80–90 s.

As depicted in Plate 1a, the spacecraft potential drops rapidly at ~0916–0934 UT, corresponding roughly to a tenfold decrease in plasma density and denoting the location of the plasmapause. Accordingly, the EMIC wave growth region extended from the outer plasmasphere through the whole plasmapause up to the plasma trough. He^+ band waves were found only in the inner edge of the plasmapause while H^+ band was strongest just outside the plasmapause. As argued by *Mursula et al.* [1997], these results are in a good agreement with earlier results on the connection of Pc1 pearls with plasmapause [see, e.g., *Roth and Orr*, 1975; *Webster and Fraser*, 1985; *Erlandson and Anderson*, 1996] and with the calculated dependence of the EMIC wave growth on plasma density in the two wave bands [*Kozyra et al.*, 1984].

Simultaneously with the Polar EMIC wave observations, the Finnish search-coil magnetometers observed two strong Pc1 pulsation bands which lasted, with variable intensity, for several hours. The dynamic spectra of the Kilpisjärvi station (KIL; 69.0° geographic latitude (GGlat), 20.9° geographic longitude (GGlong), 65.9° dipole ILAT, L = 6.0) and the Sodankylä station (SOD; 67.4° GGlat, 26.6° GGlong, 63.8° dipole ILAT, $L = 5.1$) are depicted in Plates 1c and 1d, respectively. The frequency of the stronger, lower-frequency Pc1 band matches almost perfectly with the frequency of the Polar He^+ band. Also, the frequency width of this band is very similar at both ground stations and at Polar. This is demonstrated also in Figure 2, which shows the simultaneous power spectra at SOD and Polar EFI around 0921 UT. The repetition period of the lower-frequency band at SOD is ~100 s, matching well with the repetition period of the three Polar He^+ band bursts.

The higher-frequency Pc1 band is somewhat different at the two ground stations. Moreover, the frequency width of this band on ground is considerably larger than the frequency width of H^+ band Polar EMIC waves at any given time. This is also demonstrated in Figure 2. The power spectrum of the higher-frequency Pc1 band at SOD at 0921 UT extends roughly from 1.6 to 2.3 Hz while the simultaneous spectrum of the Polar H^+ band waves are restricted to within 2.0–2.3 Hz. Accordingly, the upper Pc1 band at SOD includes additional waves which have lower frequencies than the simultaneous Polar EMIC waves. These correspond to those H^+ band waves which Polar observes slightly later after reaching higher L shells. While Polar observes waves with a rather limited frequency range on a small L range at any time, SOD observes simultaneously most of these H^+ band waves coming from a large range of L shells. Although the upper Pc1 band is structured, it is rather diffuse, and no reliable estimate for the repetition period can be obtained.

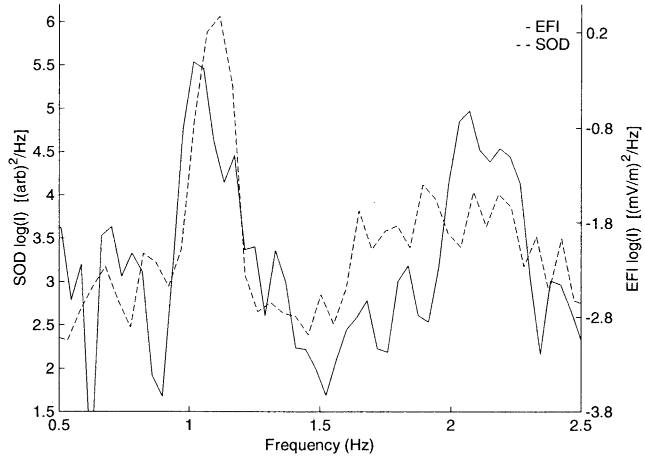

Figure 2. Power spectra of the Polar EFI y component (solid line) and SOD D component (dashed line) at around 0921 UT.

The dynamic spectra in the ULF range for some electric and magnetic field components measured by Polar EFI and MFE instruments are presented in Plate 2. Almost sinusoidal ULF waves are detected around the geomagnetic equator at ~0850 UT (56° ILAT), and some less harmonic waves are detected thereafter until ~0940 UT. The period of these long-period waves changes from ~60–70 s (15–16 mHz) at the equator to ~80–100 s (10–12 mHz) after 0910 UT, increasing with increasing invariant latitude. During the observation of the two EMIC wave bands by Polar, the period of these ULF waves coincides with the repetition period of EMIC bursts.

The Polar ULF waves are simultaneously observed on the ground by the International Monitor for Auroral Geomagnetic Effects (IMAGE) magnetometer network stations. The power spectra of EFI and several IMAGE stations are presented in Figure 3. All ground stations have a spectral peak in the period range of

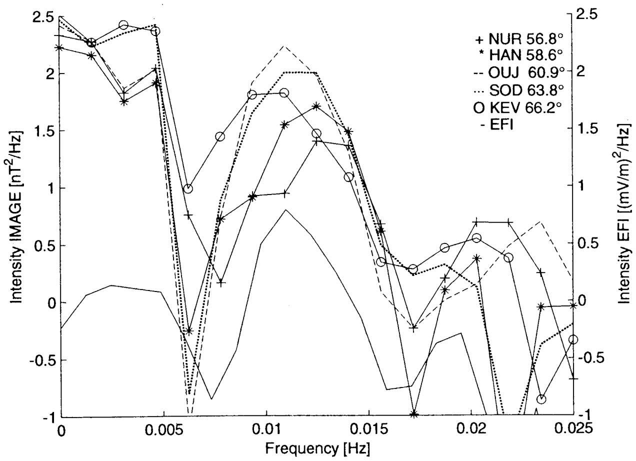

Figure 3. Power spectra of Polar EFI x component (solid line) and of the H component of several International Monitor for Auroral Geomagnetic Effects (IMAGE) ground stations at ~0920 UT. Dipole latitudes of each station are noted.

~70–100 s (10–14 mHz). The maximum power in this frequency range is observed at Oulujärvi (OUJ) station (60.9° GMlat), which is closest to the latitude of the Polar satellite during the ULF observations at 0910–0920 UT (60.5°–62.0° ILAT). We would also like to note that the two stations at latitudes lower than OUJ (Nurmijärvi (NUR) and Hankasalmi (HAN)) have their spectral peak at a slightly higher frequency, fairly close to the frequency of the ULF waves observed by Polar around the equator.

4. Latitudinal Width and Coherence of EMIC Waves

The Polar EMIC waves consist of two pearl bands which are partly colocated in space at the inner edge of plasmapause. The three bursts of the Polar He^+ band extend from $L = 4.3$ to $L = 4.6$, covering an invariant latitude range of less than 1.0° ILAT. On the other hand, the H^+ band extends over a considerably larger range of L values from 4.3 to 6.2, corresponding to ~5.2° ILAT. The latitudinal width of the EMIC source region was studied earlier by satellite observations in the topside ionosphere by the Freja satellite [*Mursula et al.*, 1994] and at midaltitudes by the Viking satellite [*Mursula et al.*, 1997]. In these studies the source region of structured Pc1s was found to be limited to less than 1.0° ILAT. *Mursula et al.* [1997] suggested that such a narrow width of the EMIC source region at low altitudes and midaltitudes may be either because of a latitudinally narrow wave source region or because the waves are guided along the magnetic field line from high to low altitudes only on a narrow L range, for example, by appropriately located plasma density gradients.

The present observations show that EMIC wave source region at high altitudes can extend over a very large latitude range of more than 5° ILAT. Ground observations show that the waves from the whole wide L range can propagate simultaneously to the ground. Moreover, the different parts of the Polar H^+ band seem to propagate fairly close to the magnetic field line from Polar to ground, sustaining their latitudinal ordering during propagation. This is verified by observations at the different ground stations. At the KIL station (see Plate 1c), north of SOD, the lower frequencies of the upper Pc1 band have a considerably larger intensity than the higher-frequency part of this band, corresponding to the fact that KIL is closer to the higher-latitude source of the low-frequency part of the Polar H^+ band. On the other hand, at stations south of SOD (not shown), the higher frequencies of the upper Pc1 band are more intense. Since all the EMIC waves having their source at a wide range of L shells, even outside the plasmapause in the plasma trough, can reach to the ground, the results suggest that plasma density gradients are not crucial for wave propagation from high altitudes to the ground.

Although the present study shows that EMIC waves can be generated at a very wide range of invariant latitudes, we would like to note that the source region generating coherent bursts of EMIC waves with a fairly constant frequency is much more limited in latitude. As noted above, the coherent He^+ band bursts were limited to within 1.0° ILAT. The same is true for the first three bursts of the H^+ band, where the frequency is constant and the burst repetition is systematic. After 0925 UT only isolated EMIC bursts at different frequencies, or EMIC activity with no clear structure are seen until at the end of the H^+ band. There, at ~0942–0948 UT, a few weak but fairly regular bursts are observed. The latitudinal width of the coherent burst region is again limited to less than ~1.0° ILAT. Note also that on ground, especially at SOD, the broad upper Pc1 band consists of several simultaneous bands with a rather narrow frequency range. Occasionally, some of these subbands do show a fairly coherent pearl structure, although no clear pearl structure is observed over the whole broad frequency range of the upper band at any time. These features of the upper Pc1 band on ground correspond very well to the above discussed Polar observations.

5. ULF Waves

Polar EMIC waves were accompanied by simultaneous long-period ULF waves observed on ground and in space. Polar observed almost sinusoidal ULF waves at about 15 mHz at the equator and slightly weaker and less regular ULF waves at higher magnetic and invariant latitudes at a lower frequency. During the strong Polar EMIC bursts at ~0920 UT the ULF wave period was ~90–100 s (10–11 mHz), matching well with the repetition period of Polar EMIC bursts and the pearls observed simultaneously on ground. Moreover, ULF waves with the same period were observed at sev-

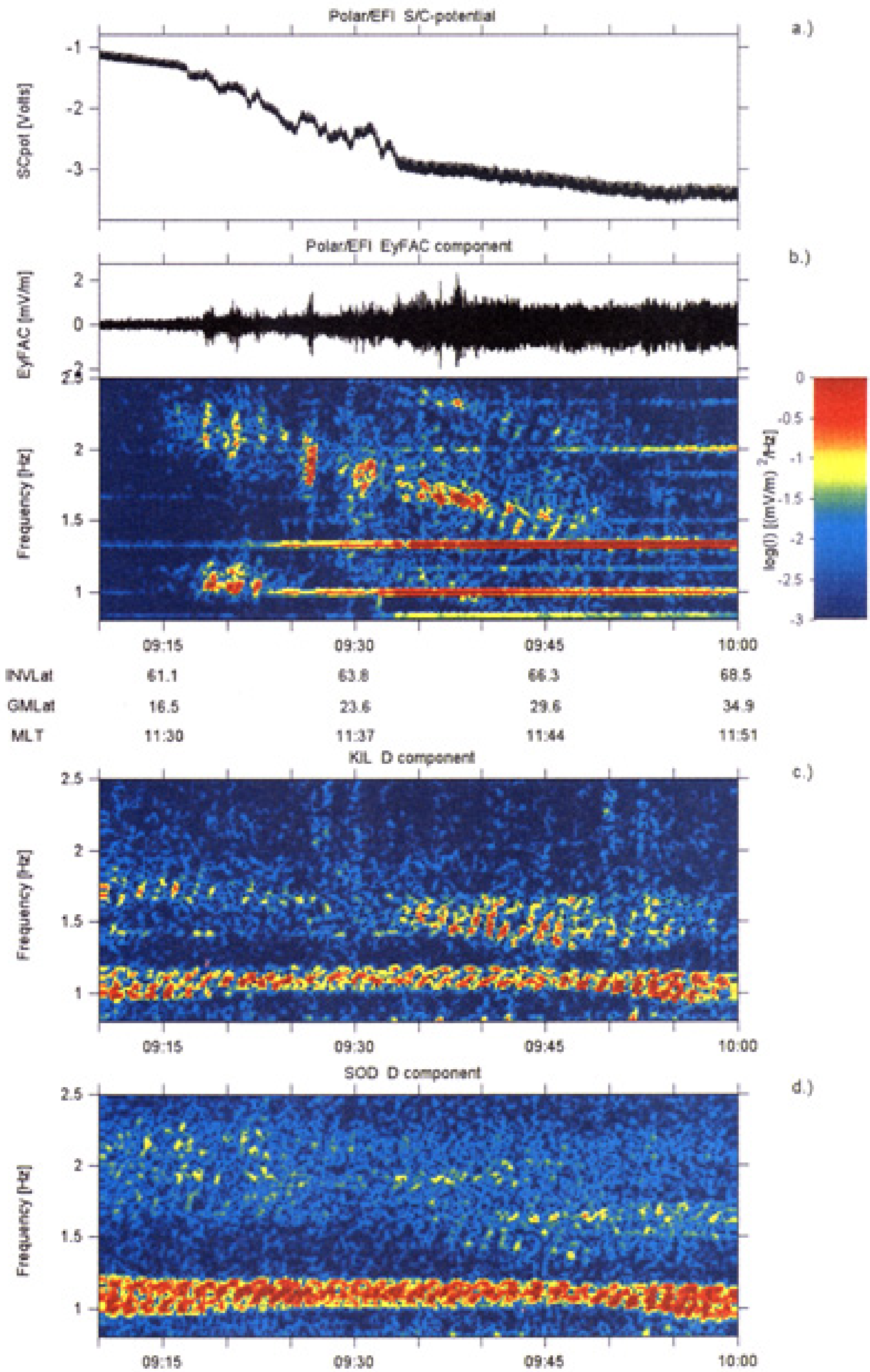

Plate 1. Polar satellite and ground observations on April 25, 1997. (a) Spacecraft potential measured by Polar Electric Field Investigation (EFI) instrument. (b) Wave form and dynamic spectrum of the Polar EFI y component at 0900–1000 UT (horizontal lines are residuals of the satellite spin period). (c, d) Dynamic spectra of the D component at Kilpisjärvi (KIL) and Sodankylä (SOD) stations.

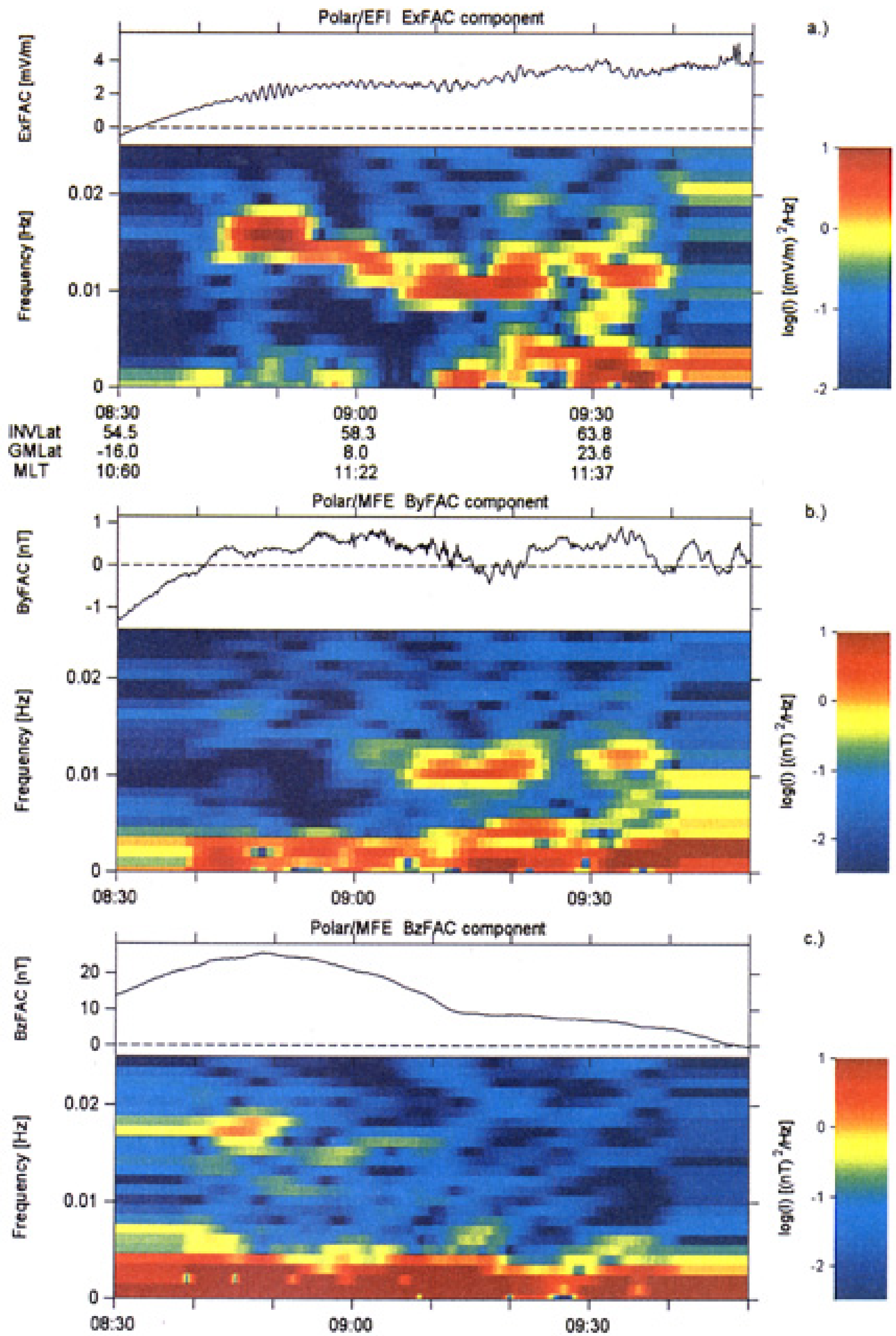

Plate 2. Wave forms and dynamic spectra of Polar field observations at ~0830–1000 UT. (a) Electric field x component. (b) Magnetic field y component. (c)Magnetic field z component.

eral ground stations simultaneously (see Figure 3), with maximum intensity at the OUJ station, which has almost the same invariant latitude as Polar at the time of the corresponding ULF waves.

These results strongly suggest that the generation of coherent EMIC bursts and the corresponding Pc1 pearls on ground is related or even due to the effect of ULF waves on the generation of EMIC waves. Evidence in support of this idea has been presented in a number of earlier studies [*Plyasova-Bakounina et al.*, 1996; *Rasinkangas et al.*, 1994; *Mursula et al.*, 1997, 1999; *Rasinkangas and Mursula*, 1998]. As proposed by *Mursula et al.* [1997, 1999], the ULF waves may modulate the growth rate of EMIC waves by affecting plasma close to marginal stability against ion cyclotron instability [*Gail*, 1990]. Interestingly, simultaneously with the most clearly coherent EMIC bursts and ULF waves at ~0920 UT, we also observe fluctuations in plasma density measured by the spacecraft potential (see Plate 1a). These fluctuations have the same period as the simultaneous ULF waves and verify that, indeed, there were notable variations in plasma density at the time and location of EMIC wave bursts. The EMIC wave bursts seem to occur in the increasing or maximum phase of density. Slightly later, at ~0925–0935 UT, somewhat stronger but more irregular density fluctuations occurred. The two largest increases of density coincided with the two strongest EMIC wave bursts observed by Polar, giving additional evidence for the modulation of EMIC wave growth by ULF waves via plasma density changes.

As an addition to the above discussion on the latitudinal width of EMIC waves, we would also like to note that the regular ULF waves with constant frequency (see, e.g., Plate 2b) and the regular plasma density fluctuations (see Plate 1a) are confined to only a rather narrow latitude range of ~1.2° ILAT. This suggests that the above mentioned latitudinal coherence of EMIC waves is determined by the corresponding latitudinal extent of coherent ULF waves, which, again, is mainly determined by the radial distribution of plasma close to the plasmapause region.

As concluded above, plasma gradients do not seem to be necessary for wave propagation. However, the modulating effect of ULF waves on EMIC wave growth is largest in a situation where large radial plasma gradients exist. Accordingly, this gives a possibility for a new explanation to the well-known connection between Pc1 pearls and the plasmapause. Contrary to the earlier view, this connection is not because of the effect of plasma gradients on wave propagation [*Mazur and Potapov*, 1983] but rather on EMIC wave growth via the ULF modulation effect.

The ULF waves at 0920 UT had the main power in the poloidal x component of the electric field (Plate 2a) and the azimuthal y component of the magnetic field (Plate 2b). This suggests that these ULF waves are mainly toroidal field line resonances. However, some amount of the poloidal mode was also found, especially in the azimuthal component of the electric field (not shown). Note also that the waves exist over a fairly large invariant latitude range and have a period which increases systematically with increasing latitude for 0850–0920 UT. These waves are probably of the fundamental harmonic mode since the electric field is stronger at the equator at ~0850 UT than at higher magnetic latitudes at 0920 UT, but the magnetic field is almost extinct at the equator.

We note that the mode structure at the equator was somewhat different from that at 0920 UT. Although the electric field had power in both transverse components, the azimuthal component was strongest, indicating that several wave modes have coexisted at the equator. Note also that a weak compressional component of the magnetic field was observed at the equator (Plate 2c). It is likely that the azimuthal electric field component is, by the E cross B drift, responsible for radial plasma density variations and thereby also for EMIC wave modulation. The slightly different mode structure at the equator and off-equator, at the higher magnetic latitude of ~20° MAGlat, also suggests that a partial mode conversion of ULF waves takes place between these locations.

6. Transit Times and Velocities

The transit time of wave bursts from the satellite to the ground can be used to estimate the group velocity of waves. We have compared the three bursts of the Polar He^+ band to simultaneous pearls at SOD. The smoothed envelopes of the respective waveforms are presented in Figure 4. An average time delay of 43 s for the three bursts is obtained from the maximum of the cross-correlation function (CCF) between the two envelopes. The accuracy of the CCF maximum is very good, a few seconds only. Moreover, the CCF time delay is found to be the same for unsmoothed and smoothed envelope curves with different smoothing lengths. Using the field line length of ~3.7 R_E calculated according to the Tsyganenko 1989 model [*Tsyganenko*, 1989] from Polar to the ionosphere, this transit time yields an average group velocity of ~550 km s^{-1}. In addition, a rough estimate for the phase velocity of EMIC waves can be obtained from the ratio of the electric and magnetic amplitudes of the wave. For the two first bursts we find ratios between 400 and 600 km s^{-1}, in accordance with the above estimate for group velocity.

The group velocity obtained here is somewhat smaller than found in earlier studies at lower altitudes. *Erlandson et al.* [1996] extracted a transit time of 12 s and an average group velocity of ~1000–1100 km s^{-1} using the Viking satellite at 64° ILAT, and 50° magnetic latitude. In another Viking study [*Mursula et al.*, 1997] at a slightly lower magnetic latitude (45°) but higher L shell (6.3–5.6), a somewhat longer transit time of 15–20 s and a lower wave velocity of 800–1000 km s^{-1} were obtained. The present Polar results are obtained from considerably higher altitudes and lower magnetic

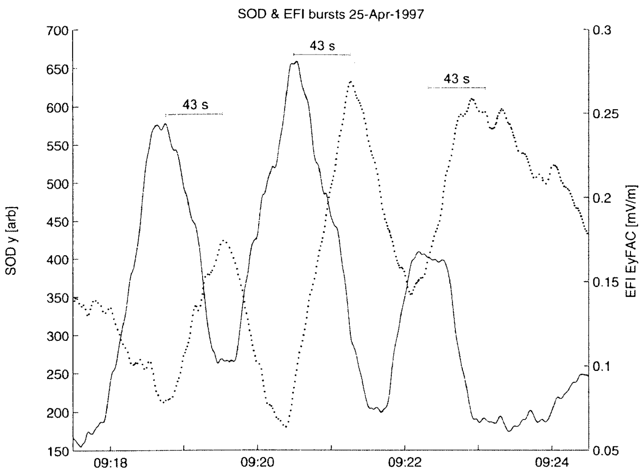

Figure 4. Envelope curve of the amplitude of the filtered signal (0.8–1.2 Hz) of the Polar He^+ band electromagnetic ion cyclotron (EMIC) wave bursts (solid line) and of the Pc1 pearls observed at SOD (dotted line) at ~0920 UT.

latitudes. The lower velocity of Polar waves indicates that the group velocity varies along the field line, being smaller at high altitudes between Viking and Polar than at lower altitudes below Viking, as suggested earlier by *Mursula et al.* [1997]. This is also in agreement with theoretical estimates of the local Alfvén velocity [see, e.g., *Leonovich and Mazur*, 1991; *Lysak*, 1997]. Moreover, *Ludlow et al.* [1991] found delay times of 35–90 s between the DE 1 satellite close to the geomagnetic equator ($L = 4.6$) and ground in the evening MLT sector, in a fair agreement with the present observation.

Using the obtained group velocity, the resulting double-hop transit time, i.e., the full pearl repetition period, in the BWP model can be estimated. A bouncing wave packet would have to trace the altitudes below Polar in the two hemispheres 4 times, spending some 3 min already at these altitudes. The full field line length for the He^+ band waves is ~10.0 R_E according to the Tsyganenko 1989 model. Accordingly, the fraction of the double-hop path at altitudes above Polar is ~5.2 R_E. Assuming the same average velocity at these high altitudes would lead to a total time delay of ~230 s instead of the 100 s observed on ground and at Polar. Moreover, the EMIC group velocity is expected to be even slower in the vicinity of the equator, further increasing the double-hop time. The heavy ion effects (nonzero frequency effects) tend to decrease the wave group velocity close to the equator where wave frequency approaches the local heavy ion gyrofrequency [*Fraser*, 1972; *Ludlow and Hughes*, 1993]. Accordingly, the rather slow group velocity of EMIC waves excludes the BWP mechanism as a cause of the observed repetitive structure of EMIC waves and thus as the cause of ground-based Pc1 pearls.

We also note that the nearly simultaneous occurrence of the three bursts of the two EMIC wave bands at ~0920 UT also provides evidence against the BWP model. Assuming the bursts of each of the two bands to be due to one packet, bouncing between the two hemispheres would lead, owing to the effect of dispersion on respective group velocities, to a considerable time delay of the H^+ band bursts with respect to the He^+ band waves. Instead, if the bursts are generated close to the equator, the path traversed by the waves from the equator to the site of observation is too short for a significant delay to develop between the bursts of the two EMIC bands.

7. Poynting Flux Calculations

We have calculated the Poynting flux of EMIC waves using the simultaneous measurements of magnetic and electric wave components. We note that, to our understanding, this is the first time that this calculation could be based on all the three components of both fields. The total Poynting flux and its three components are presented in Figure 5 for the Polar He^+ band waves. The two first bursts of this lower-frequency band are clearly visible and reach both a maximum total Poynting flux value of ~20–25 μW m^{-2}. The field-aligned component (P_z) dominates the other components by roughly 1 order of magnitude and thus forms most of the total Poynting flux. By far, the greater part of the field-aligned component is positive, i.e., directed away from equator. Accordingly, most of the energy related to these EMIC waves is propagating along the field line toward the ground. (The last, third burst at ~0922 UT is much weaker in the electric field and is not observed in the magnetic field at all, most likely because of the lower sensitivity of the MFE instrument. Therefore the corresponding Poynting flux is small, and its components have an arbitrary direction with zero average.) We also note that the magnetic field of the upper band waves is rather weak, reducing the possibility for a reliable estimate of the Poynting flux.

Erlandson et al. [1990] observed a primarily downward directed Poynting flux with maxima of ~10–100

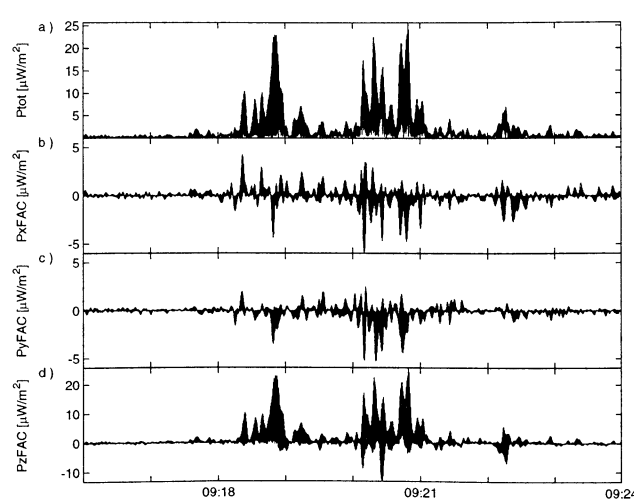

Figure 5. (a-d) The total Poynting flux of the Polar He^+ band EMIC waves and its three components. The numbers are given in units of μW m^{-2}.

μW m^{-2} using Viking satellite measurements at midaltitudes. *Erlandson et al.* [1992] studied a series of EMIC wave bursts which all had a net downward flux of a similar magnitude. The upward directed waves were not associated with downward packets and had a magnitude 5 to 10 times smaller than downward waves. *LaBelle and Treumann* [1992] also found a downward directed Poynting flux of ~3 μW m^{-2} for a weak Pc2 wave observed by Active Magnetospheric Particle Tracer Explorer (AMPTE) Ion Release Module (IRM) satellite close to the equator. Moreover, *Fraser et al.* [1996] calculated the Poynting flux for several EMIC waves observed by the CRRES satellite within ±21° magnetic latitude from equator. In most cases the wave energy was directed away from the equator with magnitudes ranging from 4 to 18 μW m^{-2}. The present value of the Poynting flux of ~20–25 μW m^{-2} and its dominantly earthward direction are in a good agreement with these earlier estimations based on a more limited set of field components. All these results limit the amount of wave power that may possibly reflect from the ionosphere and propagate toward the equator. Such waves are needed in the BWP model as a seed to generate a subsequent wave burst propagating to the opposite ionosphere. We note that wave reflection is not needed in the ULF modulation mechanism of EMIC waves. This is also in accordance with the recent finding [*Mursula et al.*, 2000] that the Pc1 frequency on the ground corresponds to the frequency of waves transmitted through the ionosphere, not reflected from the ionosphere, as dictated by the BWP model.

The two transverse components of the Poynting flux could now be calculated for the first time using the three electric and magnetic field components (see Figures 5b and 5c). Both the earthward (x) and the azimuthal (y) components of the Poynting flux show positive and negative fluctuations during the two EMIC bursts. However, while the average of the x component is roughly zero, the average of the y component is negative (eastward) with negative values being roughly twice larger than positive values. Moreover, the strongest negative values are detected when the Poynting flux has its maximum, i.e., when the Poynting flux estimate is most reliable. This indicates a small but significant azimuthal asymmetry in wave energy flux. We note that the energy flux seems to favor the direction opposite to the direction of the ions drifting from west to east. Since the EMIC wave growth is most effective when waves and ions are counterstreaming, this observation is in a good agreement with the ion cyclotron instability theory and the westward drifting of ions. We also note that the earlier measurements with fewer field components have not been able to observe this effect.

8. Conclusions and Final Notes

We have studied an event of structured EMIC waves observed by Polar satellite in good conjunction with the Finnish ground stations on April 25, 1997. Polar observed two wave bands inside and close to the plasmapause, one below the equatorial He^+ gyrofrequency, one above it. The lower-frequency, He^+ band EMIC waves consisted of clearly repetitive bursts restricted to within 1° ILAT. On the ground, this band was observed as a strong, classical Pc1 pearl band with the same frequency as Polar EMIC waves. The higher-frequency, H^+ band Polar EMIC waves occurred over a large latitude range of more than 5° ILAT. This band was observed on the ground as a broad, diffuse Pc1 pearl band with several narrower subbands. We note that strong plasma gradients do not seem to be crucial for wave propagation from high altitudes to the ground, since waves from the different invariant latitudes were guided to the ground field-aligned, even those whose source was outside the plasmapause.

The repetition period of ~100 s was the same for the Polar He^+ band bursts and ground Pc1 pearls. This is in conflict with the bouncing wave packet (BWP) model, where the repetition period on ground is expected to be twice longer than in space close to the equator. We compared the burst structure of the He^+ band waves in Polar and on the ground, finding a transit time of 43 s. This corresponds to an average group velocity of ~550 km s^{-1}, in good agreement with earlier satellite observations and theoretical expectations. However, within the BWP model this velocity leads to a pearl repetition period of ~230 s, in dramatic contradiction with the observed repetition period. Moreover, the bursts of the two Polar bands were roughly simultaneous with no significant or systematic dispersion, contrary to the BWP model. Accordingly, the present results indeed reject the standard bouncing wave packet model, according to which Pc1 pearls are generated by one wave packet oscillating from one hemisphere to another. We note that the strongest support for the BWP model, the alternate appearance of pearls in conjugate ionospheres [*Yanagihara*, 1963] is still in question. Some early [*Gendrin and Troitskaya*, 1965] and more recent studies [*Mende et al.*, 1980] have shown that the phase difference between the wave packets is not consistently 180°, as required by the BWP model, but can systematically deviate from it. Accordingly, this question should be reanalyzed using the more accurate methods of modern data analysis and better statistics.

The EMIC waves were accompanied by long-period ULF waves observed both by Polar and several ground stations. At the time of He^+ band EMIC wave bursts, Polar observed mainly toroidal ULF waves which had a period very close to the repetition period of the simultaneous EMIC bursts. Most interestingly, plasma density was seen to fluctuate simultaneously with a closely similar period. These results strongly suggest that ULF waves are an essential factor related to the EMIC wave packet formation, i.e., to the birth of Pc1 pearls. According to perhaps the most simple scenario, the ULF modulation model of Pc1 pearls, EMIC wave bursts are generated by the effect of ULF waves on plasma parameters, in particular on plasma density, at the equatorial growth region of EMIC waves. Even rather small relative variations in critical plasma parameters like plasma density could essentially modify the EMIC wave growth in a plasma close to marginal instability [*Gail*, 1990]. Therefore ULF waves could control EMIC wave growth by setting the plasma periodically into an unstable state against ion cyclotron instability.

An interesting note is that the observed ULF wave period (and the EMIC packet repetition period) is quite close to the one-hop bouncing time, i.e., twice the EMIC transit time from the equator to the ionosphere. In the simple ULF modulation model there is no direct connection between these two times. However, both times depend on the global distribution and properties of plasma, mainly via the Alfvén velocity, and are thereby indirectly related. Therefore the two times may well be roughly similar even in this model. However, one can also imagine another, slightly more complicated model where these two times are bound to be the same. Suppose that the reflected EMIC flux, although small compared to downward directed flux as verified here, would still be sufficient to affect the ion population and EMIC wave growth at the equator. This offers the possibility for a magnetospheric maser [*Polyakov et al.*, 1983] where the EMIC waves form a resonator between the two ionospheres. However, contrary to earlier suggestions, the maser would have to be symmetric with respect to the equator and have two simultaneous and phase-locked wave packets instead of one. Moreover, the ion population modified by the EMIC waves would excite such a ULF wave mode which would have the same period as the one-hop transit time, so as to enhance the two EMIC wave packets at the equator by its effects on equatorial plasma. Thereby a positive feedback would follow where the ULF waves and its plasma effects would be an essential part of the global instability. This modified EMIC maser-ULF wave scenario with two symmetric wave packets would also be in accordance with all facts presented here on structured EMIC waves. However, we still want to emphasize that the standard model of one bouncing wave packet, as well as its modern realization in terms of the original maser theory, is rejected by the present observations.

We have noted in this paper that the latitudinal coherence of EMIC waves is essentially the same as the latitudinal width of coherent ULF waves and is restricted to within 1° ILAT. This relation can be understood within both Pc1 pearl models including ULF waves discussed above. Also, we have noted that the ULF modulation effect is naturally strongest at the plasmapause, where large plasma density gradients exist. This allows for a new explanation for well-known connection between Pc1 pearls and the plasmapause. The same is true for the modified maser model, where the finding of the matching ULF wave mode is facilitated by the strong radial gradients.

We have also estimated the full Poynting flux of EMIC waves for the first time, using the three components of electric and magnetic fields. The magnitude of the total Poynting flux of the He^+ band waves was ~20–25 μW m^{-2}, in a good agreement with earlier estimates based on a less complete instrumentation. The Poynting flux was strongly directed downward away from the equator, in agreement with earlier satellite observations and in conflict with the standard BWP model. We also found a small but significant azimuthal asymmetry in wave energy flux with preference toward east, i.e., opposite to the direction of the ions drifting from west to east.

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