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

K. Marsini, T. Brișyų, 1 and K. Niskala
Department of Physical Sciences, University of Oulu, Oulu, Finland

C. T. Russell
Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California USA

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\textsuperscript{+} band waves consisted of repetitive bursts which were observed on ground as a classical Pc1 pearl band. H\textsuperscript{+} band waves occurred over a large latitude range of more than 5\degree in 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\textsuperscript{+} band bursts and ground Pc1 pearls, in conflict with the bouncing wave packet (BWP) model. Comparing the burst structure of He\textsuperscript{+} band waves in Polar and on ground, we found a transit time of ∼45 s and an average group velocity of ∼500 km s\textsuperscript{-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 frequency of EMIC waves for the first time, using the three components of electric and magnetic fields. The magnitude of the total Poyniot flux of the He\textsuperscript{+} band waves was ∼20–25 μW m\textsuperscript{-2} and strongly directed downwar downward away from the equator.

1. Introduction

Pc1 pulsations are electromagnetic ion cyclotron (EMIC) waves in the 0.1–5.0 Hz frequency range, generated in the equatorial magnetosphere by protons and heavier ions in the energy range of ∼10–100 keV [Brice, 1965; Cowley, 1969]. 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 the bouncing wave packet (BWP) model [Ohguti, 1995], the repetitive structure of pearl pulsations is generated by a wave packet bouncing back and forth the field line between opposite hemispheres, losing part of its energy when reflecting from the ionosphere 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 [Ishihara et al., 2001].

1Now at Centre for Wireless Communications, University of Oulu, Oulu, Finland.

Copyright 2001 by the American Geophysical Union.
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 (FACs) points in the direction of the Earth's magnetic field vector at the spacecraft location, positive y axis (FACs) lies in the plane of the Earth's magnetic field passing through the spacecraft's location and points toward the Earth, and positive z axis (FACs) completes the right-handed orthogonal system, pointing roughly westward.

3. Observations

Figure 1 shows the field line projected footprint of the northward bound track of the Polar satellite on April 25, 1997, crossing the invariant latitudes between ~65° and 65° at 0800-1000 UT in the 1130 magnetic local time (MLT) sector. Throughout this time the Polar footprint was in a fair conjunction with the Finnish search-coil magnetometer network. Since the satellite crosses L shells very quickly close to its perigee, the Northern Hemisphere (NH) footprint can be used to cover the perigee observations.

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). The 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.

2. Observational Setting

The Electric Field Investigation (EFI) instrument [Hickey 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 sampled 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., 1995; Bğsp sy and Mursula, 2001].

et al., 1996; Mursula et al., 1997, 1999, 2000; Rainikangas and Mursula, 1998]. According to this model, the marginally stable plasma [Guz, 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. Erlangsdottir et al. [1991] observed a band of structured waves by the Viking satellite at L = 3.5-4.1 in the premagnetc sector, and Erlandsdottir et al. [1996] observed one at L = 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 a 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 Polaris charged 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 [Rainikangas and Mursula, 1998]. In this paper we study structured Polaris 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. [1996]. 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.
The two wave bands are organized by the equatorial helium cyclotron frequency $F_{He}$, the lower band $F_{He}$ and the upper band $F_{He}$ at a frequency of $\sim 1.0-1.2$ Hz. The three most intensive bursts of this band occurred at 0918-0923 UT and had a maximum peak-to-peak amplitude of $\sim 1$mV m$^{-1}$. The repetition period of the higher band between $F_{He}$ and $F_{He}$ 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 $F_{He}$ band was $\sim 4$mV m$^{-1}$. The repetition period of the bursts of the $F_{He}$ 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 $F_{He}$ band was irregular, until at the end of the burst from 0940 UT onward, the burst structure was again more regular with a repetition period of $\sim 80-90$ s.

As depicted in Plate 1a, the spacecraft potential drops rapidly at $\sim 0916-0934$ 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 plasmapause through the whole plasmapause up to the plasma trough. $He$ wave bands were found only in the inner edge of the plasmapause while $He$ 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 Pcl1 events with plasmapause [see, e.g., Roth and Orr, 1975; Webster and Prather, 1985; Elwood and Anderson, 1991] and with the calculated dependence of the EMIC wave growth on plasma density in the two wave bands [Koszynski et al., 1984].

Simultaneously with the Polar EMIC wave observations, the Finnish search-coil magnetometers observed two strong Pcl1 pulsation bands which lasted, with variable intensity, for several hours. The dynamic spectra of the Kpajjajari station (KIL, 69.0° geographic latitude (GGLong), 26.3° geographic longitude (GGLong), 56.9° dipole ILAT, $L = 6.0$) and the Sodankylä station (SOD, 67.6° GGLong, 26.0° GGLong, 63.8° dipole ILAT, $L = 5.1$) are depicted in Plates 1c and 1d, respectively. The frequency of the stronger, lower-frequency Pcl1 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 EPI at 0921 UT. The repetition period of the lower-frequency band at SOD is $\sim 100$ s, matching well with the repetition period of the three Polar $He$ band bursts. The higher-frequency Pcl1 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 $He$ band Polar EMIC waves at any given time. This is also demonstrated in Figure 2. The power spectrum of the higher-frequency Pcl1 band at SOD at 0921 UT extends roughly from 1.6 to 2.3 Hz, while the simultaneous spectrum of the Polar $He$ band waves are restricted to within 2.0-2.3 Hz. Accordingly, the upper Pcl1 band at SOD includes additional waves which have lower frequencies than the simultaneous Polar EMIC waves. These correspond to those $He$ 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 more of those $He$ band waves coming from a large range of $L$ shells. Although the upper Pcl1 band is structured, it is rather diffuse, and no reliable estimate for the repetition period can be obtained.

The dynamic spectra in the ULF range for some electric and magnetic field components measured by Polar EPI and MFI instruments are presented in Plate 2. Almost sinusoidal ULF waves are detected around the geomagnetic equator at $\sim 0850$ UT (66° ILAT), and some less harmonic waves are detected thereafter until $\sim 0940$ UT. The period of those long-period waves changes from $\sim 60-70$ s (16-17 mls) at the equator to $\sim 80-100$ s (10-12 mls) after 0910 UT, increasing with increasing invariant latitude. During the observation of the two EMIC wave bands by Polar, the period of those 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 EPI and several IMAGE stations are presented in Figure 3. All ground stations have a spectral peak in the period range of
~70–100 s (10–14 mHz). The maximum power in this frequency range is observed at Oulu–Jyväskylä (OUJ) station (60.9° GMlat), which is closest to the latitude of the POLAR satellite during the DUF observations at 0900–0920 UT (06.5°–02.0° 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 plasma sheet. The three bursts of the POLAR H+ band extend from L = 4.3 to L = 4.6, covering an invariant latitude range of less than 1° ILAT. On the other hand, the H+ band extends over a considerably larger range of L values from 4.3 to 6.3, corresponding to ~0.2° 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 midlatitudes by the Viking satellite [Mursula et al., 1997]. In these studies the source region of structured Pcs waves 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 latitudes and midlatitudes may be either because of a latitudinal narrow wave source region or because the waves are guided along the magnetic field line from high to low latitudes 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 latitu-
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 Solankylä (SOD) stations.
Plate 2. Wave forms and dynamic spectra of Polar field observations at ~0830–1000 UT. (a) Electric field $z$ component. (b) Magnetic field $y$ component. (c) Magnetic field $z$ component.
eral ground stations simultaneously (see Figure 3), with maximum intensity at the OUV 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 Pci peaks 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 [Piiyama-Bakunina et al., 1996; Rzieckowska et al., 1994; Muruda et al., 1997, 1999; Rieutord & Rieutord, 1999]. As proposed by Muruda 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 [see 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 additional evidence for 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 plasmasphere 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 of the well-known connection between Pci peaks and the plasmasphere. Contrary to the earlier view, this connection is not because of the effect of plasma gradients on wave propagation [Mazar & 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 z component of the electric field (Plate 2a) and the azimuthal p 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 0050-0920 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 on both legs, only one of the 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 z cross B drift, responsible for radial plasma density variations and thereby also for EMIC wave modulations. 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 waves 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 peaks at SOD. The observed timing of the three peaks was 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 Rg 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 [Muruda et al., 1997] at a slightly lower magnetic latitude (45°) but higher L shell (6.3-6.6), 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 H\textsuperscript{+} band electro-magnetic ion cyclotron (EMIC) wave bursts (solid line) and of the Pc1 pearls observed at SOD (dotted line) at \textasciitilde0920 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., Leonard and Mann, 1991; Lyons, 1997]. Moreover, Ludlow et al. [1994] found delay times of 15-20 s for the DE 1 satellite close to the geomagnetic equator (L = 4.6) and ground in the evening MFT 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 H\textsuperscript{+} band waves is \textasciitilde10.0 R\textsubscript{E} according to the Tagaenko 1989 model. Accordingly, the fraction of the double-hop path at altitudes above Polar is \textasciitilde6.2 R\textsubscript{E}. Assuming the same average velocity at these high altitudes would lead to a total time delay of \textasciitilde230 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 [Forsyth, 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 \textasciitilde0920 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\textsuperscript{+} band bursts with respect to the H\textsuperscript{+} 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 H\textsuperscript{+} band waves. The two first bursts of this lower-frequency band are clearly visible and reach both a maximum total Poynting flux value of \textasciitilde20-25 \textmu W m\textsuperscript{-2}. The field-aligned component (P\textsubscript{\textit{z}}) dominates the other components by roughly 1 order of magnitude and thus forms most of the total Poynting flux. By far, the greatest part of the field-aligned component is positive, i.e., directed away from the equator. Accordingly, most of the energy relates to those EMIC waves propagating along the field line toward the ground. (The last, third burst at \textasciitilde0922 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 MFR 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.

Briendson et al. [1992] observed a primarily downward directed Poynting flux with maxima of \textasciitilde16-100
\( \mu W \text{ m}^{-2} \) using Viking satellite measurements at mid-latitude. Ertasdom 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. Labbe and Treumann [1992] also found a downward di- rected Poynting flux of \(<3 \mu W \text{ m}^{-2} \) for a weak Pcf 2 wave observed by Active Magnetospheric Particle Tracer Explor er (APMTE) 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 satellites within \( \pm 21^\circ \) magnetic latitude from equator. In most cases the wave energy was directed away from the equator with magnitudes ranging from 1 to 18 \( \mu W \text{ m}^{-2} \). The average value of the Poynting flux of \(<20-25 \mu W \text{ m}^{-2} \) and its dominantly Earthward direction are in a good agreement with those 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 BWB 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 mod- ulation mechanism of EMIC waves. This is also in ac- cordance with the recent finding [Murakawa et al., 2000] that the Pcf frequency on the ground corresponds to the frequency of waves transmitted through the ionosphere, not reflected from the ionosphere, as dictated by the BWB model.

The 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 neg- ative fluctuations during the two EMIC bursts. How- ever, while the average of the \( x \) component is roughly zero, the average of the \( y \) component is negative (east- ward) with negative values being roughly twice larger than positive values. Moreover, the strongest negative values are detected when the Poynting flux has max- imum, i.e., when the Poynting flux estimate is most re- liable. This indicates a small but significant azimuthal asymmetry in wave energy flux. We note that the en- ergy 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 the- ory 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 ob- served two wave bands inside and close to the plasma- pause, one below the equatorial He+ gyrofrequency, one above it. The lower-frequency, He+ band EMIC waves consisted of clearly repetitive bursts restricted to within \( \pm 20^\circ \) of the ground; this band was observed as a strong, classical Pcf1 band with the same fre- quency as Pola EMIC waves. The higher-frequency, H11 band Polar EMIC waves occurred over a large lati- tude range of more than \( 5^\circ \) from the equator. This band was ob- served on the ground as a broad, diffuse Pcf1 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 field-aligned.

The repetition period of \(<100 \mu s \) was the same for the Polar He+ band and ground Pcf1 peaks. This is in conflict with the bouncing wave packet (BWP) model, where the repetition period on ground is ex- pected 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 tran- sit time of 43 s. This corresponds to an average group velocity of \(<550 \text{ km s}^{-1} \) in good agreement with ear- lier satellite observations and theoretical expectations. However, within the BWP model this velocity leads to a peak repetition period of \(<230 \mu s \), in dramatic contra- diction with the observed repetition period. Moreover, the bursts of the two Polar bands were roughly simulta- neously with no significant or systematic dispersion, con- trary to the BWP model. Accordingly, the present re- sults indeed reject the standard bouncing wave packet model, according to which Pcf1 peaks are generated by one wave packet de-oscillating from one hemisphere to an- other. We note that the strongest support for the BWP model, the alternate appearance of peaks in conjugate ionospheres [Yamagishi, 1992] 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 reassessed using the more accurate methods of modern data analysis and betting 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 simulta- neous EMIC bursts. Most interestingly, plasma density was seen to fluctuate simultaneously with a closely sim- ilar period. These results strongly suggest that ULF waves are an essential feature related to the EMIC wave packet formation, i.e., to the birth of Pcf1 peaks. Ac- cording to perhaps the most simple scenario, the ULF modulation model of Pcf1 peaks, EMIC wave bursts are generated by the effect of ULF waves on plasma parame- ters, in particular on plasma density, at the equatorial
growth region of EMIC waves. Even rather small rela-
tive variations in critical plasma parameter like plasma
density could essentially modify the EMIC wave growth
in a plasma close to marginal instability [Gaz, 1990].
These variations could be represented by setting the plasma
periodically into an unstable state
against ion cyclotron instability.

An interesting note is that the observed ULF wave
period (=the EMIC packet repetition period) is quite
close to the one-hop bouncing time, i.e., twice the EMIC
wave transit time from the equator to the ionosphere.
In effect, the ionosphere is a mirror of the
connection between these two times. However, both
times depend on the global distribution and propor-
tion of plasma, mainly via the Alfvén velocity, and are
thereby inherently related. Therefore the two times may
well be roughly similar in this model. However, one
can also imagine another, slightly more compli-
cated 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 popu-
lation and EMIC wave growth at the equator. This
offers the possibility for a magnetospheric maser [Poljakov
et al., 1983] where the EMIC waves form a resonator be-
tween the two ionospheres. However, contrary to ear-
er 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. More-
over, the ion population modified by the EMIC wave
would excite such a ULF wave mode, which would last
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. Thus a positive feed-
back 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 sce-
nario with two symmetric wave packets would also be in
disaccord 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 co-
herence 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 Pcl pearl models including ULF waves dis-
cussed above. Also, we have noted that the ULF mod-
elation effect is naturally strongest at the plasmapause,
where large plasma density gradients exist. This
allows for a new explanation for well-known connection
between Pcl pearls and the plasmapause. The same is
true for the modified maser model, where the finding
of the matching ULF 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 compo-
nents of electric and magnetic fields. The magnitude of
the total Poynting flux of the Ho band waves was ~20-
25 μW m⁻², in a good agreement with earlier estimates
based on a less complete instrumentation. The Poynt-
ing flux was strongly directed downward away from
the equator, in agreement with earlier satellite observations
and in conflict with the standard EWP model. We also
found a small but significant azimuthal asymmetry in
wave energy flux with preference toward east, i.e., op-
posite to the direction of the ions drifting from west to
east.

Acknowledgments. The Academy of Finland is ac-
knowledged for financial support. We acknowledge NASA
grant FNC65-079 to support the CIRI field Poynting vector
observations. Janet G. Luhmann thanks Rudolf A. Treumann and an-
other referee for their assistance in evaluating this paper.

References
Brice, N., Generation of very low frequency and hydromag-
Biky, T., and K. Murusula, Grand-satellite observations of
Caswell, J. M., Cyclotron instabilities and electromagnetic
emissions in the ultra low frequency and very low fre-
Eriksen, R. B., and R. J. Anderson, Pc 4 waves in the
ionosphere: A statistical study, J. Geophys. Res., 101,
7853-7867, 1996.
Eriksen, R. B., R. L. J. Zanetti, A. T. Pettersen, L. P. Block,
and G. Fomsgaard, Viking magnetic and electric field ob-
servations of Pc 4 waves at high latitudes, J. Geophys.
Eriksen, R. B., R. B. Anderson, and L. J. Zanetti, Viking
magnetic and electric field observations of periodic Pcl
waves: Pearl pulsations, J. Geophys. Res., 97, 14,832-
Eriksen, R. B., K. Murusula, and T. Bissing, Simultane-
on ground-satellite observations of structured Pc 4 pul-
Fraser, B. J., Propagation of Pc 1 micropulsations in a
proton-helium magnetosphere, Planet. Space Sci., 50,
Fraser, B. J., R. H. Steger, W. J. Humphries, J. G. Wygars,
and M. S. Oke, Structure and evidence for a CIRI field
Poynting vector observations of electromagnetic ion cyclotron waves near
the plasmapause, J. Geophys. Res., 101, 15,331-15,344,
1996.
Gall, W. B., Theory of electromagnetic cyclotron wave
growth in a time-varying magnetosphere, J. Geophys.
Res., 95, 18,095-18,097, 1990. *.
Gendrin, R., and V. A. Troitskaya, Preliminary results of
a micropulsation experiment at conjugate points, J. Res.
Harvey, P. et al., The electric field instrument on the Polar
Korotki, U. T., E. Craven, A. P. Nagy, E. P. Ponteboim,
and R. S. B. Ong, Effects of energetic heavy ions on elec-
romagnetic ion cyclotron wave generation in the plas-
LaBelle, J., and R. A. Treumann, Poynting vector mea-
surements of electromagnetic ion cyclotron waves in
Leonovich, A. S. and V. A. Mazur, An electromagnetic field,
defined in the ionosphere and atmosphere and on the
Earth's surface by low-frequency Alfvén oscillations of the
Yanagihara, K., Geomagnetic micropulsations with periods from 0.03 to 10 seconds in the auroral zone with special reference to conjugate-point studies, J. Geophys. Res., 68, 3383-3397, 1963.
T. Brkić, Center for Wireless Communications, FIN-90014 University of Oulu, Finland. (e-mail: time.brkic@oulu. fi)
K. Mursula and K. Nisula, Department of Physical Sciences, FIN-90014 University of Oulu, Finland. (e-mail: Kati.Mursula@oulu. fi)
C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90025.
(Received September 22, 2000; revised May 25, 2001; accepted June 26, 2001.)