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Modulation of magnetospheric EMIC waves by Pc 3 pulsations of upstream origin

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Abstract. We recently [*Mursula et al.*, 1997] studied a series of bursts of electromagnetic ion cyclotron (EMIC) waves observed by the Viking satellite and on ground, and showed that these bursts can not be explained by the bouncing wave packet model. Here we show that the burst structure is due to simultaneous Pc 3 waves of upstream origin.

Introduction

Magnetospheric electromagnetic ion cyclotron (EMIC) wave activity is occasionally structured in time domain, showing either well developed pearl type wave packets (mainly at low and mid-latitudes) or more chaotic bursts (especially at higher latitudes). The pearl type Pc 1 pulsations have traditionally been explained with the bouncing wave packet (BWP) model [*Jacobs and Watanabe*, 1964; *Obayashi*, 1965], in which a wave packet travels back and forth along a field line between ionospheric mirror points. Energy losses in the ionospheres are thought to be compensated by subsequent equatorial wave growth.

However, several observations cast strong doubts on the BWP model. The ionospheric reflection of pearl type wave packets observed at mid-altitudes has been estimated to be rather small [*Erlandson et al.,* 1992]. Poynting vector calculations using the CRRES satellite data have shown that the wave packets are propagating predominantly away from the equator [*Fraser et al.*, 1996]. Recently *Mursula et al.* [1997; hereafter referred to as Paper 1] studied a structured EMIC wave event detected by the mid-altitude Viking satellite and on ground, and showed that the repetitive EMIC bursts observed by Viking can not be explained by the BWP model. Instead, they suggested that the EMIC bursts are due to the effect of simultaneous longer period ULF waves. The possibility of EMIC wave growth modulation by Pc 3-5 pulsations has been discussed, e.g., by *Fraser et al.* [1992], *Rasinkangas et al.* [1994], and *Plyasova-Bakounina et al.* [1996].

In this paper we will present detailed observations of long period ULF waves during the EMIC burst event studied in Paper 1. We will show that Pc 3 waves of upstream origin are most likely the source for the observed burst structure of magnetospheric EMIC waves.

Observations

The event studied in Paper 1 occurred on April 11, 1986, when a Pc 1 wave event was registered by the Finnish search-coil magnetometer network (see Table) during several hours from about 0600 UT onwards. At 0650 - 0657 UT, the polar orbiting Viking satellite flew closely over the network at 09 MLT and altitude of 13000 km, registering several EMIC wave bursts (Figure 1). The strongest waves were observed in two separate wave regions at L values 6.2 and 5.7, with frequencies of about 0.3 and 0.5 Hz, respectively. The burst repetition period was about 43 seconds. In Paper 1 we presented a detailed analysis to show that this repetition period is too short to be in accordance with the BWP model.

Figure 2 displays the simultaneous magnetic registrations at the IVA station. The two upper panels show the wave forms of the H and D components, displaying strong long period waves. The bottom panel (see also Plate 1 of Paper 1) shows the wave form of the D component band-pass filtered in the frequency band between 0.25 and 0.35 Hz which corresponds to the frequency of the first Pc 1 region observed by Viking. The ground (Figure 2) and Viking (Figure 1; see also Paper 1) Pc 1 signals are modulated by roughly the period of the long period waves. On ground these Pc 3 waves started already on the previous day at about 2300 UT and continued during most of the day in question at all stations. They were strongest at IVA and weakest at KIL, and although seen in both H and D components, the latter was often dominating. During the Viking flyby the frequency was about 22 mHz (T = 45 s), as seen in Figure 3 (upper panel; note that the power at KIL is much weaker than elsewhere at this time, which explains the poor peak shape).

Simultaneous Pc 3 wave activity was recorded by IMP-8 upstream of the bow shock (Figure 4). Power spectrum calculated over one hour period around the Viking event peaked at 18 - 25 mHz (40 - 56 s; Figure 3, lower panel). Just before the event the IMP-8 wave frequency was close to the high-frequency edge of this range (Figure 4 at 0650 UT; the dashed vertical lines indicate the midpoint of the Viking event). Closer analysis has shown that these waves were transverse left-hand circularly polarized waves. During the event, IMP-8 was located at [26, -23, 9] R_e GSM, and the average IMF was about [-4, 2, -0.5] nT GSM. Solar wind speed was about 360 km/s. The wave activity at IMP-8 started at about 2300 UT on the previous day when the IMF cone angle ($\Theta_{xB} = \cos^{-1}(B_x/|B|)$) dropped from 40-50° to 20-30°; this correlation was evident also later during the event.

Table 1. The ground based stations with their geographic locations and L values. MLT is calculated for 0650 UT.

Ground based stations					
Code	Station	GG lat	GG long	L	MLT
KIL	Kilpisjärvi	69.0	20.9	6.0	9:04
IVA	Ivalo	68.7	27.3	5.6	9:23
ROV	Rovaniemi	66.8	25.9	4.7	9:13

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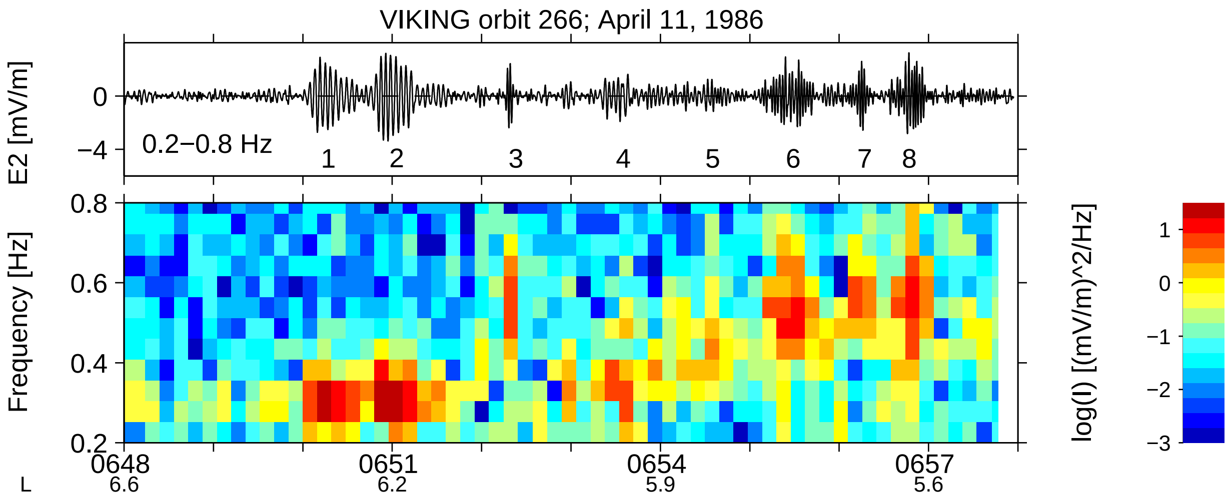

Figure 1. The EMIC wave bursts observed by Viking in the perpendicular ele ctric field component. The two separate wave source regions are seen from the difference in wave frequency at higher (left-hand side) and lower latitudes (right-hand side).

During the Viking event the geosynchronous GOES-6 (107.8°W) satellite was close to the midnight sector, and did not register any wave activity. However, well before the event, at around 2300-0100 UT, GOES-6 observed two separate wave bands centered at 17 and 24 mHz (59 and 42 s; data not shown). During this time the satellite was in the afternoon local time sector. The higher frequency band was again observed (although weakly and for a short time) at about 1800 UT when the satellite rotated to the late morning sector of the Viking event (Figure 3, lower panel). The higher frequency pulsations were azimuthally polarized, i.e., were seen mainly in the D component, while waves at 17 mHz were seen in all three components.

Also Viking registered weak Pc 3 waves in the perpendicular (nearly poloidal) electric field component, E2 (Figure 3, lower panel, calculated around 0655 UT). The relative weakness of the Viking signal is understandable since the satellite was crossing the L shells very fast. If the waves were concentrated only on a small range of L shells, the Viking observation time remained short.

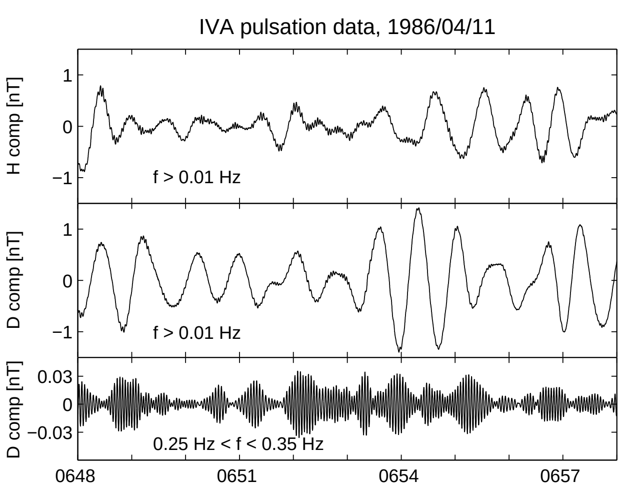

Figure 2. Search-coil magnetometer data from the IVA station during the Viking Pc 1 event. The two upper panels show the Pc 3 waves in the two components (DC trend has been removed); the bottom panel shows the the ground Pc 1 waves in the frequency range of the first Viking Pc 1 region.

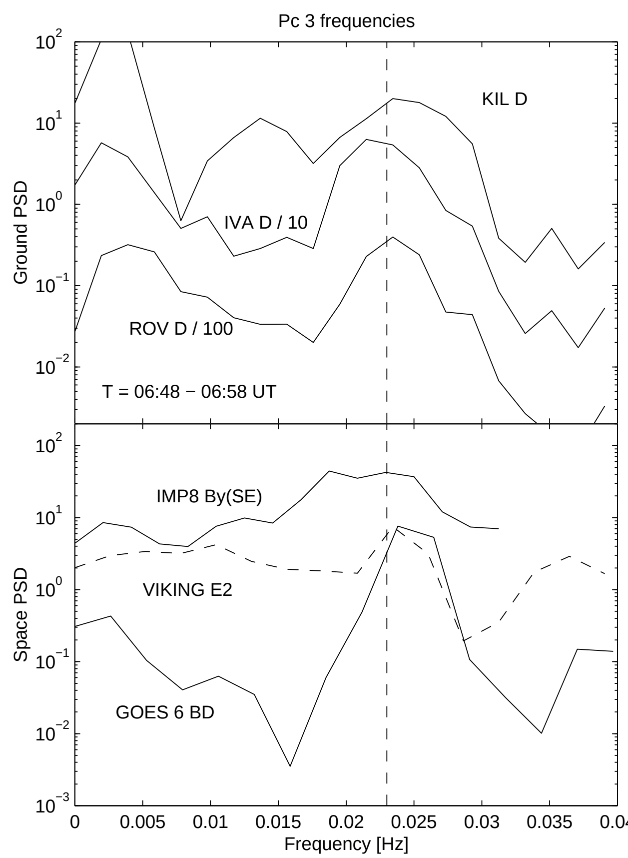

Figure 3. Selected power spectra from the ground (upper panel) and space (lower panel). The vertical dashed line corresponds to 23 mHz (43 s).

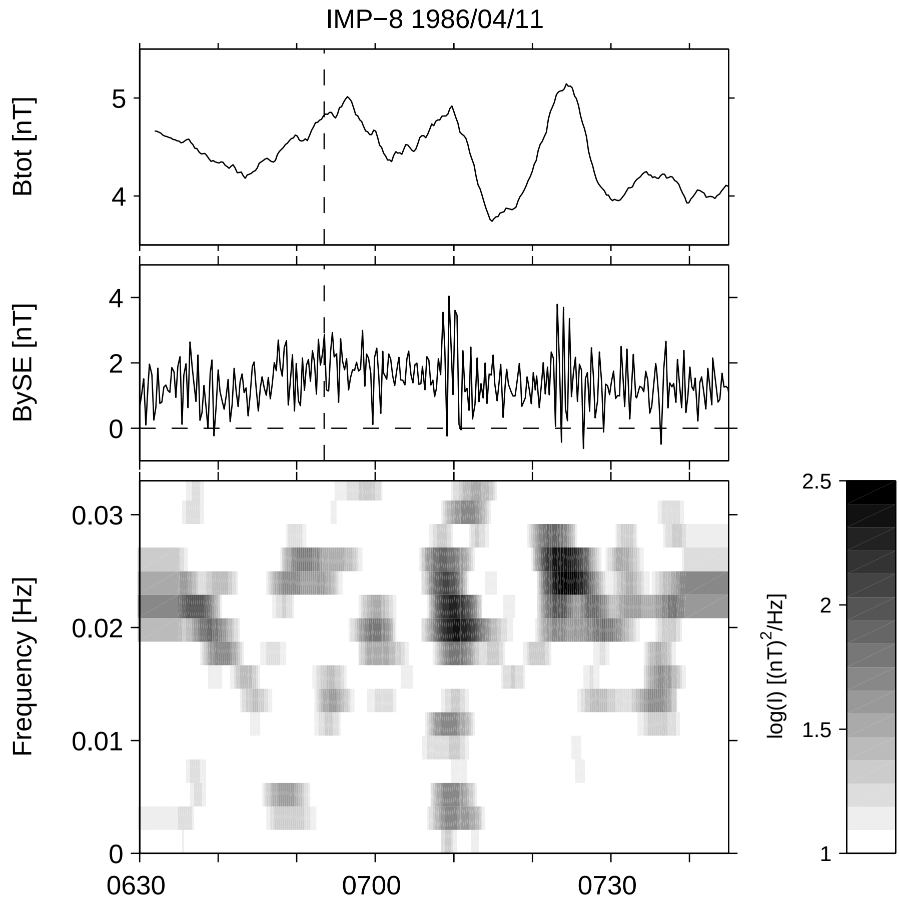

Figure 4. IMF strength (floating average over 5 min) and higher resolution waveform and spectrogram of the upstream wave activity around the Viking event (0650 - 0657 UT; midpoint is indicated by the dashed vertical lines).

Discussion and conclusions

During the present event, IMP-8 was well located to measure upstream waves, being in the late morning MLT sector of quasi-parallel bow shock. The IMF cone angle controlled the IMP-8 Pc 3 wave activity, enhancing it when low. This may be due to the IMP-8 location, favoring upstream wave observation for cone angles somewhat smaller that the nominal, or due to the dependence of wave growth on the cone angle [e.g., *Paschmann et al.*, 1979]. (Note also that IMP-8 was located rather high above the ecliptic. Even stronger waves are expected closer to the ecliptic.)

The average IMF strength, 4.5 nT, gives f = 20 - 34 mHz (T = 29 - 50 s) from the well known equation f [mHz] = $(6\pm1.5) \times$ B [nT] for waves of upstream origin [*Yumoto et al.*, 1985; earlier *Guglielmi*, 1974; *Russell and Hoppe*, 1981]. Waves of corresponding frequency (about 24 mHz, 42 s) were seen not only in the upstream region, but also at geosynchronous orbit, mid-altitude Viking satellite, and on ground (Figure 3). They appeared in IMP-8, GOES-6, and ground based data late on the previous day, and seemed to permeate most of the dayside sector by the time of Viking observation of Pc 1 bursts.

The frequency of these Pc 3 waves corresponds extremely well with the repetition period of the EMIC bursts observed by Viking (Figure 1; for a detailed analysis, see Paper 1). Similar modulation of Pc 1 amplitude was observed on ground as well (Figure 2) although ducting of waves from different field lines may seriously affect modulation and phase pattern there. This strongly implies that the repetition period of EMIC waves was determined by the longer period waves. We suggest that the Pc 3 waves modulate the equatorial growth rate of EMIC waves. It has been shown that rather small changes in relevant plasma parameters (e.g., plasma density) are enough to cause large variations in wave growth in marginally stable plasmas [Gail, 1990].

The Pc 3 waves observed by GOES-6 were mainly toroidal, field line harmonic type waves that are probably mode converted from the compressional Pc 3 waves of upstream origin. However, the GOES-6 measurements were not simultaneous with Viking observations, and were observed in a different MLT sector. Moreover, the fact that the Pc 3 waves observed on the ground during Viking flyby were somewhat stronger in the D component than H component suggests that the corresponding magnetospheric waves were not purely toroidal but also had a considerable poloidal component. The unfortunate lack of simultaneous observations at the equatorial region makes it impossible to determine the exact mode of the hydromagnetic wave responsible for the modulation of EMIC waves. No further information is received from Viking either since the other transverse electric field component is missing.

The frequencies of the Pc 3 waves at different L shells (4.7 - 6.6, from ROV to GOES-6) agreed generally quite well with each other and remained within the spectral width of the upstream waves observed by IMP-8. This suggests that the waves inside the magnetosphere were rather directly driven by the upstream waves, without significant modification due to the different eigen-frequency at different L shells [*Verö and Miletits*, 1994]. However, the ground based Pc 3 waves do show an overall trend of slightly lower frequencies of Pc 3 waves at higher latitudes. (A small difference is seen between IVA and ROV even in Figure 3, but KIL is much weaker and shows an opposite trend at this time.) This supports the finding in Paper 1, that the Pc 1 repetition period is slightly (by 10%) longer at the higher latitude (L = 6.2) source than at the lower latitude source (L = 5.7). Such a variation is very well in accordance with the field line resonance model and the difference in field line lengths may well produce the differences of observed magnitude.

Concluding, compelling evidence suggests that the EMIC wave bursts observed by the Viking satellite inside the magnetosphere were modulated by magnetospheric Pc 3 waves of upstream origin. Since it was shown earlier [*Mursula et al.*, 1997] that the bouncing wave packet model can not explain the observations, the Pc 3 modulation remains as the only viable model in accordance with observations. Since the upstream and other long period ULF waves are very common, it is plausible to suggest that the ULF modulation mechanism is working very often and forms a serious alternative to the bouncing wave packet model.

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