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Dispersive Pc1 bursts observed by Freja

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Abstract. Electric field measurements by the Freja double probe sensor are used to study equatorially generated ion cyclotron waves, also called Pc1 pulsations. We have examined the global occurrence and spectral properties of these waves in the upper ionosphere during 12-hour period on Nov. 18, 1992, when a long chain of structured Pc1 waves (pearls) was observed on ground. In agreement with ground observations, Pc1 waves were found to occur as short bursts of 10-25 s in early morning to postnoon MLT sector. Most Pc1 activity was detected within a small latitudinal range, extending from 60° CGMlat at dawn to 63° CGMlat at noon. The latitudinal width of the source was only about 0.5° CGMlat. Observations give evidence for a plasmapause connected source region that was several hours wide in MLT and active during many hours. One burst displayed a fully developed classical dispersive Pc1 pearl, now detected for the first time above the ionosphere. In all studied Pc1 events, two spectral maxima (bands) were observed. The longer Pc1 wave bursts showed evidence for a small time delay between the lower and upper frequency bands, unveiling a new dispersive phenomenon.

Introduction

Electromagnetic ion cyclotron waves (Pc1 pulsations) have been extensively studied since their first observation in 1936 [*Harang*, 1936; *Sucksdorff*, 1936]. Pc1 waves observed on ground have been classified according to their morphological structure [*Fukunishi et al.*, 1981]. One of the most common Pc1 types are the pearl pulsations (structured Pc1's) which consist of periodic emissions of wave bursts or pearls. Pearl pulsations are the dominant form of Pc1 activity at low latitudes [*Fraser-Smith*, 1970] and form a fair fraction at high latitudes [*Fukunishi et al.*, 1981; *Mursula et al.*, 1993]. They are thought to be due to wave packets propagating from one hemisphere to another [*Jacobs and Watanabe*, 1964; *Obayashi*, 1965] close to the plasmapause [*Fraser et al.*, 1984] where appropriate conditions for wave guidance are found [*Mazur and Potapov*, 1983].

Satellite observations of structured Pc1's are very rare. Repetitive Pc1 pearls have been reported by *Perraut* [1982] and *Erlandson et al.* [1992], both presenting only one event. The former event was observed close to equator by GEOS-2, the latter in mid-altitude magnetosphere by the Viking satellite. Furthermore, *Iyemori and Hayashi* [1989] observed a few short non-repetitive Pc1 bursts in the ionospheric F-region on the Magsat satellite.

The Freja satellite with its 600 km*1750 km orbit is complementary to the deeply ionospheric or high-altitude satellites allowing Pc1 waves to be studied above but close to the expected ionospheric reflection and mode conversion region. With its 63° inclination, Freja spends more time than polar spacecraft at mid- to subauroral latitudes, thus providing a better coverage of some regions such as plasmapause. The short orbital period of 110 minutes enables one to study the global extent and time development of the Pc1 source region in steps of about two hours.

In this paper we present the first results on the global occurrence and detailed spectral properties of Pc1 waves, as observed by the Freja F1 double probe electric field instrument [*Marklund et al.*, 1994]. We have used the so called overview mode of the F1 instrument which samples data nearly continuously over several successive orbits. Overview mode resolution of 8 samples/s is enough to study the Pc1 frequency range. In addition to electric field, F1 provides information on plasma density and its variations from the spacecraft floating potential (Vfg) as measured by the average potential of a boom pair.

Observations

We have studied F1 overview data in November 18, 1992, when the Finnish search coil magnetometer network (extending from L=3 to L=6 at about MLT=UT+2.5 h) observed Pc1 pearl activity nearly continuously from about 0130 until 1400 UT. Judging from wave amplitudes at these stations, the source of activity was rather close to L=4-5. Freja orbit had its apogee (perigee) close to midnight (noon), being thus fairly symmetrical with respect to dawn and dusk (see Fig. 1). We analyzed about 12 hours of overview data from 02 to 14 UT, i.e. most of the time when ground Pc1 activity was observed. During this time, the orbit changed such that the highest latitudes attained by Freja close to its apogee (perigee) decreased from 75° (-78°) to 60° (-53°) CGMlat.

Four main bursts (events a-d) of Pc1 activity were detected. Their orbital location is depicted in Fig. 1 and their properties are summarized in Table. Event b occurred just after apogee, all other events close to perigee (event d exactly at perigee). Events covered a longitude range from 03 to 14 MLT, and remained at fairly similar latitudes from 60° to 63° CGMlat. During two events (a and d), the satellite was within 1h MLT from the stations while during the other two events the MLT difference was larger, about 3-4 h. (In addition, two other events of sporadic wave activity were observed at higher latitudes).

We have studied the spectral features of the four Pc1 events. Figures 2 and 3 depict the wave form and dynamic spectra of the two longer events (c and d). In all four events, spectral power was seen to form two bands with more power in the lower band. The frequency range of these two bands are given in Table. Table also shows the equatorial He^+ gyrofrequency calculated using the Tsyganenko 1989 model [*Tsyganenko*, 1989]. In three events (a, b and d) the lower band was clearly below the He^+ gyrofrequency. In event c, the lower band was cut into two by a spectral slot at the He^+ gyrofrequency (see Fig. 2). (Note, however, that the calculated value of He^+ gyrofrequency for event c may be 50% higher if the satellite longitude was in error of only 10°).

Note that the harmonics of the spin rate (spin period is 6 s), especially the second and fourth harmonics at 0.33 and 0.67 Hz, remain at some level in the data even after subtracting the spacecraft rotation (see Fig. 2). This may make the detection of low-frequency Pc1's more difficult, but here all the events

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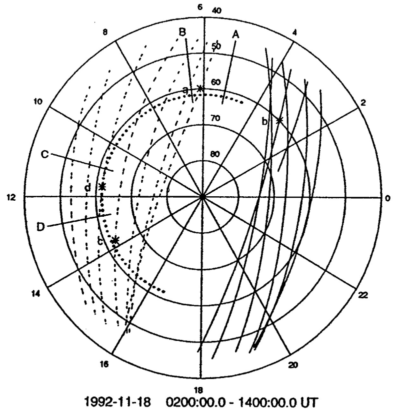

Figure 1. Freja orbits on Nov. 18, 1992, from 02 to 14 UT depicted in a polar plot with constant CGMlat values as circles and constant MLT values as sectors. (Orbit traces are drawn above 45° CGMlat only). Solid (dashed) lines correspond to the pass in the northern (southern) hemisphere. Perigee and apogee latitudes constantly decrease with time during the period. The track of the location of Oulu station (61.8° CGMlat, 107° GMlong) during this period is shown as a chain of small circles. Crosses indicate the four Pc1 events (a-d) and capital letters (A-D) depict the MLT location of Oulu during the corresponding events.

were at higher frequencies. Note also that spacecraft spinning causes a Doppler spreading of the spectra by ±1/6 Hz [*Erlandson et al.*, 1992]. Frequency ranges given in the Table have not been corrected for this effect and thus overestimate the true spectral widths by this amount.

The three longer events (b-d) give evidence for a small time difference between lower and higher frequencies, the latter occurring towards the end of event. This new dispersive phenomenon is most dramatically seen in event c where two separate wave bursts are observed with a time delay of about 5 s (see Fig. 2). The first burst was longer and stronger, and had a lower frequency. The second burst was shorter, and had most wave power at about 2.3 Hz, in fair agreement with the higher frequency band of other events. From the ratio of time difference (about 15 s) and frequency difference (1.5 Hz) between the two bursts, one can estimate the slope of dispersion to be about 10 s/Hz. (Zero value corresponds to no dispersion). Slightly smaller but similar values can be obtained also for events b and d.

Another, more common type of dispersion is seen in event d where the lower band (below 1.3 Hz) has a rising frequency (see Fig. 3). Estimating the frequency rise to be about 0.2 Hz within 10 s at around 1011:30 UT, one obtains a dispersion slope of about 50 s/Hz. We have depicted in Fig. 4 the integrated power spectrum for event d, as well as for two pearls observed (nearly) simultaneously by a nearby ground station.

Event	a	b	c	d
Time (UT)	0243	0355	0826	1011
Duration (s)	10	13	20	24
MLT (h)	6	3	14	12
CGMlat (°)	-60	60	-63	-62
ΔCGMlat (°)	0.47	0.53	0.46	0.11
Max. ampl. (mV/m)	4.0	1.5	2.5	4.0
f_{low} (Hz)	0.75-1.45	0.7-1.3	0.6-1.4	0.7-1.3
f_{high} (Hz)	1.9-2.4	2.4-2.8	2.0-2.6	1.7-2.0
$F_{eq}(He^+)$ (Hz)	1.9	1.6	1.0	1.3

Table. Detailed properties of the four main Pc1 events (a-d): time of occurrence, duration, MLT time, latitude, range of latitudes passed during the event, maximum amplitude in any of the two components, frequency ranges of lower and upper wave bands, and equatorial He$^+$ gyrofrequency.

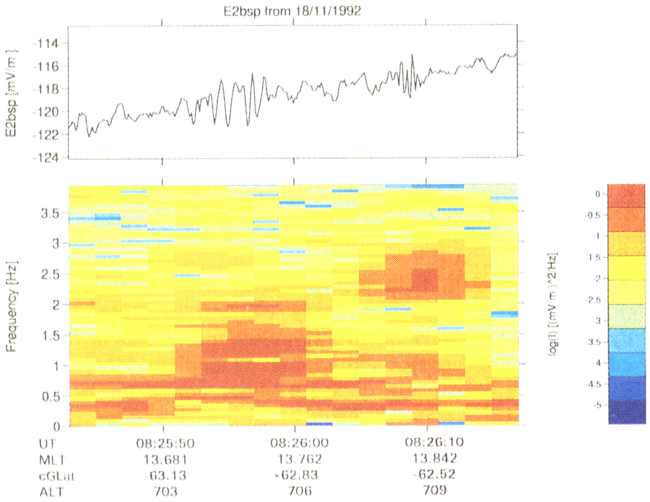

Figure 2. Wave form and colour coded spectral density (over the whole spectral range 0-4 Hz) for event c (E2 component; E1 is along the projection of magnetic field onto spin plane and E2 is perpendicular to it).

Note also that the early MLT events (a and b) occurred close to a clear dropout in Vfg by about 10% (see Fig. 5). Although it is difficult to determine the plasmapause location at low altitudes, at least in the dusk sector (see e.g. *Green et al.*, 1986), such a large scale dropout may be associated with plasmapause. A smaller, more local depletion (about 2%) was observed during event d, and none for event c.

Discussion

A. Global occurrence properties. The MLT range of Pc1 bursts observed by Freja (03-14 MLT) was clearly dawn-dusk asymmetric and in accordance with maximum occurrence of pearl pulsations in the morning [see e.g. *Saito*, 1969] and the present ground observations. Freja observed event b at earlier MLT than on ground, indicating a westward expansion of the Pc1 source. The large MLT difference (3-4 hours) between Freja and simultaneous ground observations during events b and c gives evidence for a wide longitudinal extension of the Pc1 source. Note that in event d with a conjunction of about 1h MLT, slightly different frequencies were observed at Freja and on ground (see Fig. 4). For other events, similar or even larger differencies were observed. Thus it seems that the ground station observes waves from several Pc1 active field lines with

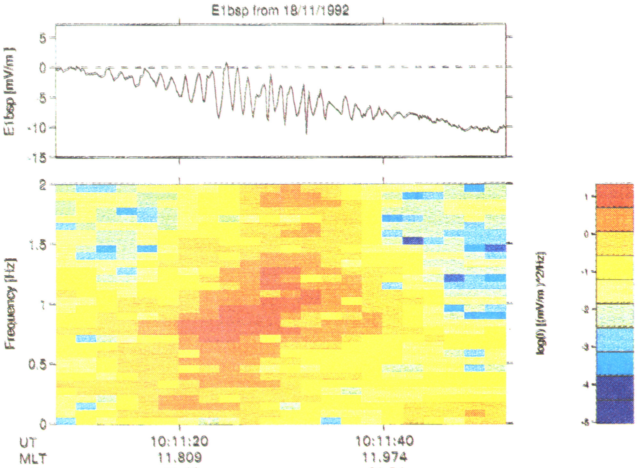

Figure 3. Wave form and spectral density (0-2 Hz) for event d (E1 component).

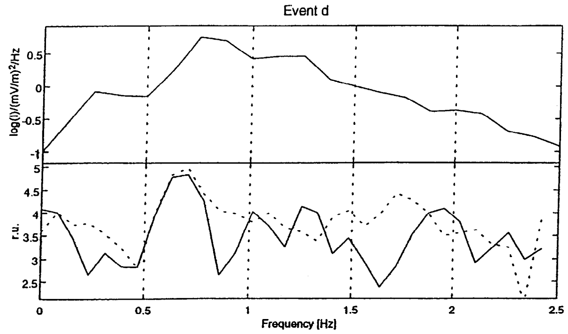

Figure 4. Logarithm of integrated power for Freja d-event (upper panel) and for observations at Oulu simultaneously (lower panel, solid line) and one minute later (dashed line). (Ground-based power is in relative units).

slightly different frequencies. Ducting may also affect this difference between Freja and ground station.

Interestingly, all four main Pc1 events were detected at almost constant latitudes, with a small systematic increase from 60° CGMlat in the morning to 63° in the afternoon. This indicates a very stable situation of the Pc1 source during the 12 hours studied. The last two events occur at later MLT because the decreasing orbit reaches relevant latitudes only towards noon perigee. Despite continuous Pc1 activity observed on ground, no Pc1 events were observed at Freja after the perigee decreased below 60° CGMlat, giving additional evidence that Pc1 activity only existed above that latitude.

The latitude range of Pc1 events (60°-63°) is in agreement with the expected location of plasmapause, the probable source of pearl pulsations. The morning events (a and b) were observed close to a clear density decrease while the noon events showed only small or no density fluctuations. Two factors may contribute to this difference. First, the earlier high-latitude orbits cross plasmapause more sharply and give a more clear signal than the later lower latitude orbits which cross the plasmapause nearly tangentially. Second, the plasma- pause may be sharper in the morning than at other MLT sectors.

The observed stable pattern of Pc1 source is probably a result of quiet geomagnetic conditions, implying that no major changes e.g. in plasmapause position occurred. Daily Kp value was only 13- (3-hour values: 3-, 1, 1-, 1+, 1, 2+, 3, 1-). Dst was also very stable, varying from about -10 nT to -5 nT during observations. Thus the ring current was also stable.

B. Length of the bursts. The length of Pc1 events was steadily increasing with time. This curious feature can naturally be explained in terms of change of Freja orbit towards lower perigee and apogee latitudes during the period considered. During the first two events, Freja orbit reached much higher latitudes than during the latter events. On these high-latitude orbits, Freja crossed the Pc1 active L-shell (at about 60° CGMlat) more rapidly than on the later lower-latitude orbits when moving more longitudinally at these latitudes.

We have studied this development in more detail and calculated the width of the latitude range traversed by Freja during the Pc1 events. The latitude widths of the events are 0.47°, 0.53°, 0.46° and 0.11° CGMlat. Interestingly, the latitude ranges for the three first events are nearly equal although the observed duration of these events varied by a factor of 2. This can easily be understood if wave activity was confined to a narrow latitude range of about 0.5° CGMlat. During the first two events, Freja was not staying long enough on that narrow shell in order to detect the full Pc1 burst, only about half of the full duration. On the other hand, a whole pearl was detected in event d (where satellite was fortunately located at perigee), thus giving the true duration of (probably all) Pc1 pearls of about 25 s. (Note the well developed, soliton type form of the pearl envelope of event d). Since Freja spent in this case much more time in the narrow Pc1 shell than the duration of the pearl, this event also indicates that Pc1 activity on that shell really consisted of separate pearls rather than continuous activity.

The full pearl duration of about 25 s is well in agreement with simultaneous ground observations, and with the results by Erlandson et al. (1992) where pearl durations of 20-30 s were found. The shorter durations of the first two events are in agreement with the duration of 5-10 s of Pc1 wave packets observed by the polar orbiting, deeply ionospheric Magsat satellite [*Iyemori and Hayashi*, 1989]. The fact that even shorter bursts were found there gives additional support for our interpretation of a narrow latitude range of Pc1 activity traversed by spacecraft at different angles.

During the period studied, Freja crossed the 60° CGM latitude shell 22 times. Out of these, 11 crossings occurred in the 03-14 MLT sector where the four main Pc1 events were observed. This gives us a "hit" probability of 36%. Taking 15-20 s as an observable length of the pearl, and using the pearl repetition time of about 60 s [*Erlandson et al.*, 1992], a fairly similar value is obtained. This comparison also indicates that the narrow Pc1 shell indeed was active most of the time over the long MLT range.

C. Dispersion and other spectral properties. The changing Freja orbit also allows us to understand the differencies in the dispersion properties of the four events. It is natural that any dispersion is more clearly visible in the two latter, longer events where the full (event d) or nearly full (event c) pearl development can be followed. For shorter bursts, part of the wave is missing and the possible dispersive development is more hard to observe. The noon events (c and d) may also be more favourably located for dispersion since they are at slightly higher latitudes and thus on longer field lines than the morning events. In the bouncing wave packet theory of pearls, dispersion is explained in terms of frequency dependence of wave growth rate and propagation [*Gendrin et al.*, 1971]. The noon events have longer path and more time for dispersion to develop during propagation.

All four events had two spectral maxima, one at around 1 Hz, the other at or above 2 Hz. In three events (see Table), the equatorial He$^+$ gyrofrequency can explain this splitting [*Young et al.*, 1981]. (In event c, the calculated He$^+$ gyrofrequency matches the slot in the lower band. This value may, however, be in error by 40-50%). It is probable that the lower (higher) band corresponds to the growth region below (above) the equatorial He$^+$ gyrofrequency (cutoff frequency). In all

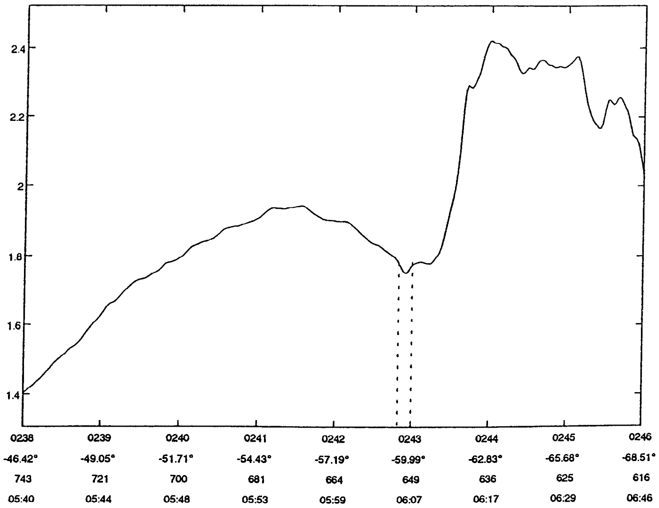

Figure 5. Spacecraft potential Vfg (in V) for event a. Vfg is logarithmically dependent on plasma density. Coordinates below the figure are UT time, CGMlat, altitude (km), and MLT. Event location (shown as dashed vertical lines) corresponds exactly to a smaller decrease in the middle of a larger dropout.

events, the spectral power of the higher band was lower than at lower frequencies.

In three longer events, the higher band appeared with a small time delay, indicating a new dispersive phenomenon. We call this "two-band dispersion", in difference to the more standard pearl dispersion observed within one band. Such behaviour was most dramatically seen in event c where the two bands were nearly completely separated. The slope of two-band dispersion was similar in the three events but smaller than the slope of standard dispersion. So far, it is not clear if such small but non-zero time delay between the two bands can be explained within the standard dispersion theory for Pc1 waves.

Another, less standard explanation for two-band dispersion is that the higher frequencies are harmonics of the lower band, being excited in the ionospheric Alfvén resonator [*Polyakov and Rapoport,* 1981] with a small time delay after the initial burst. In this scheme, a time delay of a few seconds is quite natural. In all four events, the upper band has roughly twice the lower frequency. Multi-band spectral structures have been reported e.g. in the ULF noise at mid-latitudes [*Belyaev et al.*, 1989]. Of course, more events must be studied to verify the present observations and to clarify their cause. Finally, we would like to note that the upper band of event d was observed on ground at a slightly lower frequency than at Freja. Unfortunately, the signal was too weak to determine the possible time difference.

The pearls of the (standard one-band) Pc1 pulsation events observed on ground usually have a positive dispersion slope, in agreement with theoretical expectations [*Gendrin et al.*, 1971]. Here, the ground-based pearls showed a positive but varying slope. The slope at the time of event d was about 50-100 s/Hz, corresponding quite well to the slope found for the lower band of event d and to a typical value on ground [*Gendrin et al.*, 1971]. (We note that event b also shows evidence for similar dispersion). As previous satellite observations of dispersive pearl pulsations do not exist, this is the first observation of pearl dispersion above the ionosphere and a possible verification of its magnetospheric origin. This observation may thus pose an interesting problem for such alternative theories [e.g. the ionospheric Alfvén resonator theory, *Polyakov and Rapoport*, 1981] where pearl dispersion is an ionospheric effect. Note also that the Doppler effect only widens the power spectra but does not shift the frequency of maximum power. Therefore it does not change the estimates for dispersion slope.

Conclusions

We have observed Pc1 activity in the upper ionosphere as brief bursts of different lengths (10-25 s). While the full length of a Pc1 pearl is about 25 s, the satellite occasionally misses, depending on the orbit, part of the pearl when crossing the narrow wave source region. This view also unites the earlier satellite observations [*Erlandson et al.*, 1992; *Iyemori and Hayashi*, 1989] where different burst lengths were observed.

While sporadic wave activity occurred also at higher latitudes, main Pc1 waves were found in a small latitude range (60°-63° CGMlat) but a wide longitude range (03-14 MLT). Data suggest a plasmapause connected Pc1 source region that was narrow in latitude (only about 0.5°), several hours wide in MLT and fairly stable during many hours.

We have observed for the first time above the ionosphere a fully developed dispersive Pc1 pearl with a dispersion slope in agreement with ground observations. In all four main Pc1 events, spectral density showed two maxima, one at about 1 Hz, the other at about 2 Hz. Furthermore, the three longer events showed evidence for a time delay in the appearance of the higher band, a new type of dispersive phenomenon reported for the first time.

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