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Non-stationary Alfvén resonator: new results on Pc1 pearls and IPDP events

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Abstract

We analyse a Pc1 pearl event observed by the Finnish search-coil magnetometer network on 15 December 1984, which subsequently developed into a structured IPDP after a substorm onset. The EISCAT radar was simultaneously monitoring the mid- to high-latitude ionosphere. We have calculated the ionospheric resonator properties during the different phases of the event using EISCAT observations. Contrary to the earlier results, we find that the Pc1/IPDP (Interval of Pulsations of Diminishing Period) frequency observed on the ground corresponds to the maximum of the transmission coefficient rather than that of the reflection coefficient. This casts strong doubts on the bouncing wave packet model of Pc1 pearls. Instead, we present evidence for an alternative model of pearl formation in which long-period ULF waves modulate the Pc1 growth rate. Moreover, we propose a new model for IPDP formation, whereby the ionosphere acts as an active agent in forming the IPDP signal on the ground. The model calculations show that the ionospheric resonator properties can be modified during the event so that the resonator eigenfrequency increases according to the observed frequency increase during the IPDP phase. We suggest that the IPDP signal on the ground is a combined effect of the frequency increase in the magnetospheric wave source and the simultaneous increase of the resonator eigenfrequency. The need for such a complicated matching of the two factors explains the rarity of IPDPs on the ground despite the ubiquitous occurrence of EMIC waves in the magnetosphere and the continuous substorm cycle. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The electromagnetic ion cyclotron (EMIC) waves are ubiquitous in space. In the Earth's magnetosphere/ionosphere system, they are observed in several different morphological forms when viewed from the ground. Some of the most common types are the Pc1 pearls which have been known for more than 60 years (Sucksdorff, 1936; Harang, 1936). The bouncing wave packet (BWP) hypothesis has been the standard model for Pc1 pearls for more than 30 years (Jacobs and Watanabe, 1964; Obayashi, 1965). According to this model, the repetitive bursts of EMIC waves (pearls) are produced by a wave packet traveling back and forth along a field line between two ionospheric mirror

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points. Energy loss during each ionospheric reflection is thought to be compensated by subsequent wave growth in the near-equatorial source region. Despite the considerable success of the BWP model, there are several facts which cast strong doubts on it. The ionospheric reflection of pearls observed by a satellite at mid-altitudes has been estimated to be quite small (Erlandson et al., 1992). Also, Poynting vector calculations using CRRES satellite data have shown that the EMIC wave packets are propagating predominantly away from the equator (Fraser et al., 1996). Recently, Mursula et al. (1997) studied a structured EMIC wave event detected by the mid-altitude Viking satellite and showed that the repetitive bursts could not be explained by the BWP model.

Another, but much less common, type of EMIC waves is IPDP (Interval of Pulsations of Diminishing Period) whose characteristic is a notable increase in wave frequency (Troitskaya and Melnikova, 1959) in about 15–45 minutes. IPDPs mainly occur in the evening sector (Heacock, 1973) and are closely related to the substorm expansion phase (Fukunishi, 1969; Heacock, 1971a; Roxburgh, 1970). During substorm onset on the nightside, new energetic ions are injected into the inner magnetosphere which can enhance existing or generate new EMIC wave activity along their westward drift trajectory in the evening sector. Several models have been presented in order to explain the increase in wave frequency during an IPDP event. These include enhanced radial drift of ions due to a strong electric field (Heacock, 1967; Gendrin et al., 1967), energy dispersion of the drifting ions (Fukunishi, 1969) and an increase of the background magnetic field (Roxburgh, 1970). However, all these models have difficulties in explaining some IPDP related observations. First, the electric field mechanism is most effective near midnight, but most IPDP events are observed earlier in the evening sector, many even in the afternoon where this mechanism can hardly operate. Second, the energy dispersion model, according to which the lower wave frequencies are generated first by the more energetic protons and higher frequencies later by less energetic ions, requires a considerable distance for ions of different energy to separate. Although IPDP slopes close to midnight are typically steeper than further out (Pikkarainen et al., 1983), some IPDP events observed near midnight have too small slopes to be accounted for by the energy dispersion mechanism. Also, some afternoon IPDP events are found to have very steep slopes. Third, ATS-1 satellite measurements at the time when an IPDP was observed on the ground did not detect an increase of the background magnetic field (Bossen et al., 1976).

In this paper, we discuss an interesting ion cyclotron wave event of 15 December 1984, where a classical, long Pc1 pearl series suffers, after a substorm onset, a strong increase in frequency, leading to an IPDP event consisting of pearls. During part of the event, the EISCAT radar was monitoring the mid- to high-latitude ionosphere in the same local time sector where waves were observed. It has been suggested that the ionosphere can act as a resonator for Alfvén waves (Polyakov and Rapoport, 1981), affecting the waves propagating through the ionosphere to the ground. Taking this possibility into account, we have calculated the resonator effect of the ionosphere on Alfvén waves in the present nonstationary situation, using simultaneous EISCAT observations as input to estimate the state of the ionosphere at any particular time. We find that the wave frequency observed on the ground corresponds to the maximum of the calculated transmission coefficient during the whole event, including the IPDP phase. This result is in contradiction with the earlier idea that the wave frequency corresponds to the maximum of the reflection coefficient (Belyaev et al., 1984, 1987; Feygin et al., 1994; Prikner et al., 1998) and, accordingly, also with the bouncing wave packet hypothesis. Rather, we find evidence for the modulation of the Pc1 growth rate by longer period ULF waves (see, e.g., Plyasova-Bakounina et al., 1996; Rasinkangas et al., 1994; Rasinkangas and Mursula, 1998; Mursula et al., 1999). Moreover, on the basis of the results obtained in the paper, we suggest a new scenario for the rise of wave frequency and the formation of the IPDP signal on the ground. Contrary to the earlier, purely magnetospheric models of IPDP, this scenario includes the ionosphere as an active factor.

2. Observations

The dynamic spectra of four Finnish search coil magnetometers (KEV, SOD, OUL, NUR) for 15 December 1984, from 19 to 21 UT, are shown in Fig. 1. The coordinates of all the stations used in this paper are given in Table 1. One can see a continuous structured Pc1 pearl band at all the four stations of Fig. 1 from before 19 UT to after 20 UT. We will call this part the Pc1 phase; the central frequency increases slowly from about 0.3 Hz to 0.4 Hz during this phase. The amplitude of the pearl band is strongest at the two stations in the middle (SOD and OUL) and weakest at the northernmost station (KEV). At about 2015 UT, the Pc1 band weakens and disappears at least for a while at three stations (KEV, SOD, NUR) and remains as a continuous band only in OUL. Starting at about 2030 UT, a series of PiB bursts (short, broad-band disturbances) are observed at most stations with maximum intensity in the northernmost station. After the start of these disturbances, the rise of the frequency of the Pc1 band proceeds more rapidly than during the Pc1 phase. At about 2045 UT, soon after the strongest PiB disturbance, a very fast increase of wave frequency and intensity is observed, leading to an IPDP event. (We will call the evolution from 2030 UT to 21 UT the IPDP phase.) The central frequency at the end of the event at about 21 UT is about 0.9 Hz. There are two features which make this IPDP event rather special. One is the continuity, at least at one station, of the wave band from the pre-existing Pc1 band throughout the whole IPDP development. The other is that the pearl structure remains very clear

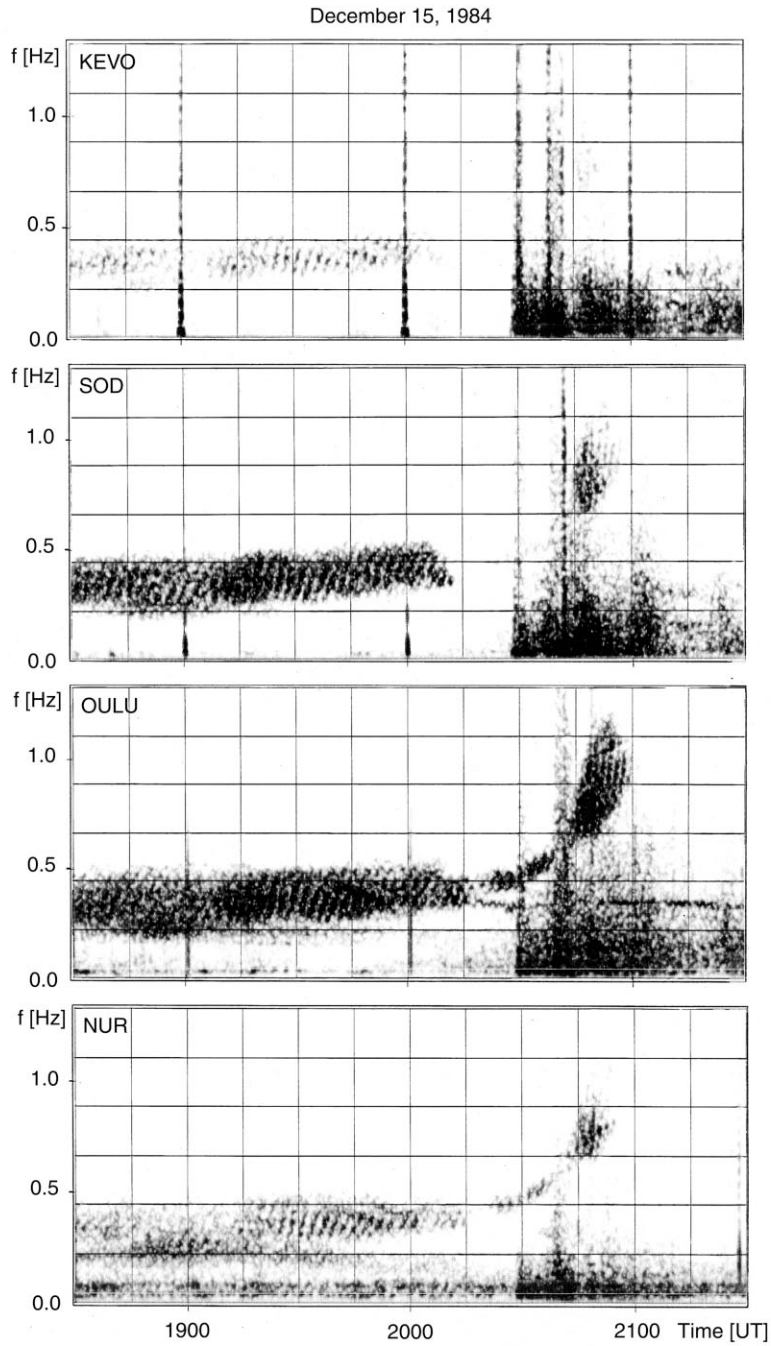

Fig. 1. The dynamic spectra of four Finnish search coil magnetometers on 15 December 1984. Kevo and Oulu depict the D-component, Sodankylä and Nurmijärvi the H-component. The same attenuation was used in each spectrum.

during the whole event. Although events of this type are rather rare, they are not unique (Maltseva et al., 1979).

The start of the Pc1 band (not shown in Fig. 1) was simultaneous with the start of an increase of the Dst index from a fairly constant level of about 22 nT until 15 UT to a positive Dst with a maximum of +6 nT at 20 UT. This increase in Dst was probably due to enhanced solar wind (SW) pressure. It is known that SW pressure pulses can effectively produce and enhance EMIC wave activity (Anderson and Hamilton, 1993). A similar event where global Pc1 pearl activity was in a good correlation with an increasing Dst was studied by Erlandson et al. (1994). Unfortunately no SW or IMF data were available at this time. After 20 UT, a substorm growth phase started, leading to the onset at about 2030 UT and a maximum AE index of about 1200 nT at 2047 UT. At onset, a very abrupt decrease of the AL index started at 2028 UT, simultaneously with the start of the PiB bursts seen in Fig. 1. However, the AU index started increasing only somewhat later at about 2041 UT and reached its maximum at 2100 UT. The period of increasing AU corresponds well to the IPDP phase with the strong increase in wave intensity and frequency.

The EISCAT radar was operated from about 1940 UT to 2045 UT in a mode (CP-3 experiment) where the radar beam was scanning along the magnetic meridian from North to South, each scan lasting about 26 minutes. Accordingly, each data point of one scan extended to a different altitude and was measuring at a different latitude at a fixed altitude. The altitude profiles of the electron density, electron temperature and ion temperature are shown in Fig. 2. One can see, e.g., that the density profiles during the first two complete scans, the first from 1940 to 2006 UT, and the second from 2010 to 2036 UT, are quite different. After the substorm onset at about 2030 UT, a dramatic increase of ionisation is seen, in particular, in the lower ionosphere below 150 km. The effect of the onset is visible over the whole latitude range, as verified by the strong ionisation at the start of the third scan at high latitudes.

3. Numerical method and results

The effect of the ionosphere on ion cyclotron waves was modelled using the matrix procedure of Prikner and Vagner (1983, 1990). The numerical simulation method presents the inhomogeneous ionosphere as a stack of fine homogeneous planar layers in a dipole background magnetic field. (For more details of the method see, e.g., Prikner and Vagner, 1983, 1990 and Prikner et al., 2000). A left-handed (Alfvénic) plane wave was taken incident on the upper boundary of the ionosphere which was assumed to be at 1000 km altitude. We used the coordinates of Oulu in the calculations for simplicity. However, results with a somewhat different magnetic field inclination (i.e., latitude) were essentially the same. The numerical simulations used the EISCAT altitude profiles of electron density, electron and ion temperature, effective ion mass and effective electron and ion collision frequency. Since EISCAT observations extended at best only up to 600 km, we used a simple exponentially decaying ionosphere above this height. Details of calculations in the present case are presented in Prikner et al. (2000).

As an output from computations we obtain the complex amplitude of the wave electric and magnetic field at any altitude of the ionosphere and on the ground. The reflection coefficient $RA(f)$ and the transmission coefficient $TA(f)$ for a certain frequency are calculated from the absolute values of the complex magnetic field amplitude (MFA) of the horizontal component. Accordingly, $RA(f)$ gives the ratio of the reflected field magnitude on the upper boundary of the ionosphere to the magnitude of the incident wave, and $TA(f)$ is the ratio between the wave transmitted to the ground and the magnitude of the incident wave. Note that RAR 1 for all frequencies, but $TA(f)$ can acquire any value because of the possibility of resonant MFA amplification in the Alfvén ionospheric resonator, see, e.g., Prikner and Vagner (1990).

Table 1

Station	Geographic coordinates		Corrected geomagnetic coordinates		
	Latitude	Longitude	Latitude	Longitude	L value
Kevo	69.88	27.08E	66.08	110.38	6.1
Kautokeino	69.08	23.08E	65.58	106.78	5.8
Sodankylä	67.48	26.68E	63.78	108.28	5.1
Oulu	65.18	25.58E	61.48	105.98	4.4
Nurmijärvi	60.58	24.78E	56.78	102.88	3.3

The $RA(f)$ and $TA(f)$ coefficients were calculated at eight different times from 2001 to 2037 UT. The selected periods were from times when the radar beam was pointing south of the zenith of Tromsø, i.e., only the lower-latitude section of EISCAT data was used in modelling, so as to better correspond with the conditions around the selected model station (Oulu). The calculated coefficients are shown in Figs. 3 and 4. In addition, since the EISCAT observations stopped before the end of the IPDP phase of the event, the coefficients were calculated during the main IPDP phase at 2054 UT, using only model values for the ionosphere. It appeared that the central wave frequency at any time was well correlated with the first minimum of the $RA(f)$ and the first maximum of the $TA(f)$ spectrum, i.e., with the fundamental eigenmode frequency of the ionospheric resonator. Recurrent computations were performed by varying the density profile at altitudes where EISCAT data were missing in order to have the best coincidence between the resonances and the wave frequency in any time sequence. However, we note that this procedure only made the agreement better. A similar procedure could not reproduce the maxima of the reflection coefficient at the central frequency of the wave band.

4. Discussion

4.1. Consequences on theories of pearl formation

Let us first discuss the implications of the result that the frequency of the wave observed on the ground corresponds to the first minimum (or maximum) of the

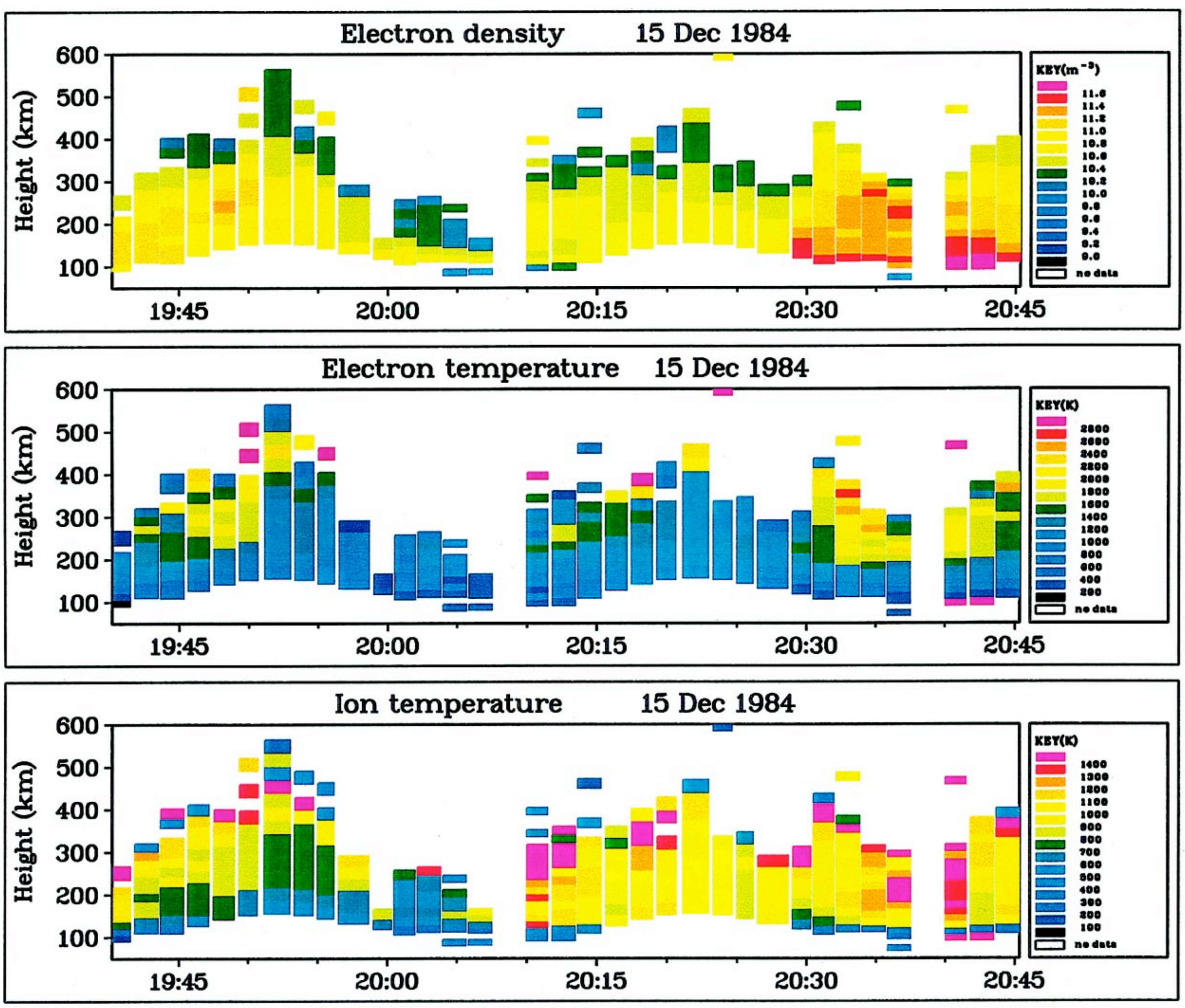

Fig. 2. EISCAT measurements of the ionosphere on 15 December 1984.

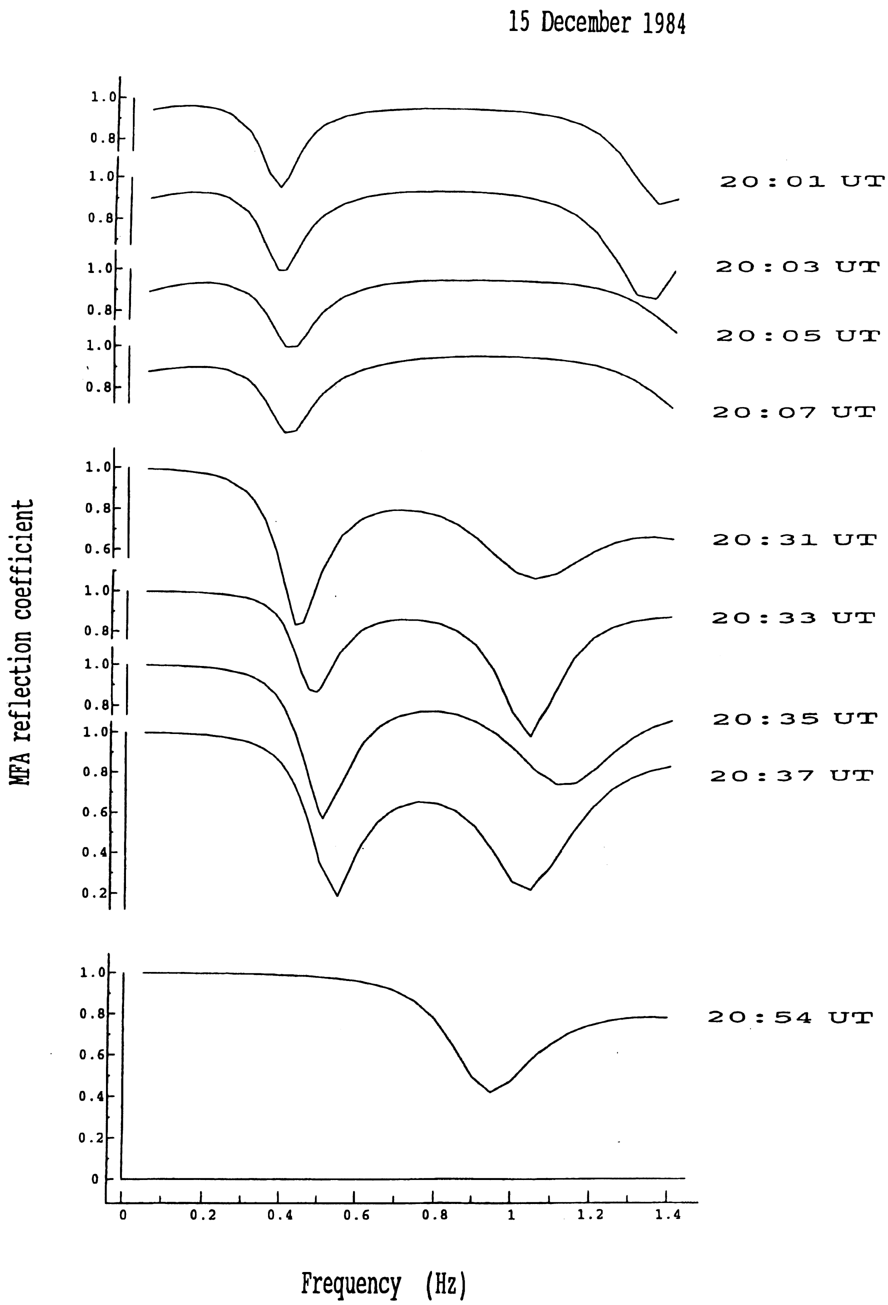

Fig. 3. The magnetic field amplitude (MFA) reflection coefficient for frequencies between 0 and 1.4 Hz modelled for nine time sections.

reflection (or transmission) coefficient, i.e., to the ionospheric resonator's first eigenmode frequency (Lysak, 1991, 1993). This result disagrees with the earlier view that the wave frequency observed on the ground corresponds to the maximum of the reflection coefficient (Belyaev et al., 1984, 1987; Feygin et al., 1994; Prikner et al., 1998). This earlier view was actually based on the requirement imposed by the bouncing wave packet hypothesis, according to which the wave can only grow at those frequencies where the ionospheric reflection is sufficient. We emphasize that this earlier view and the earlier model calculations were not based on solid experimental observations but rather on a theoretical bias.

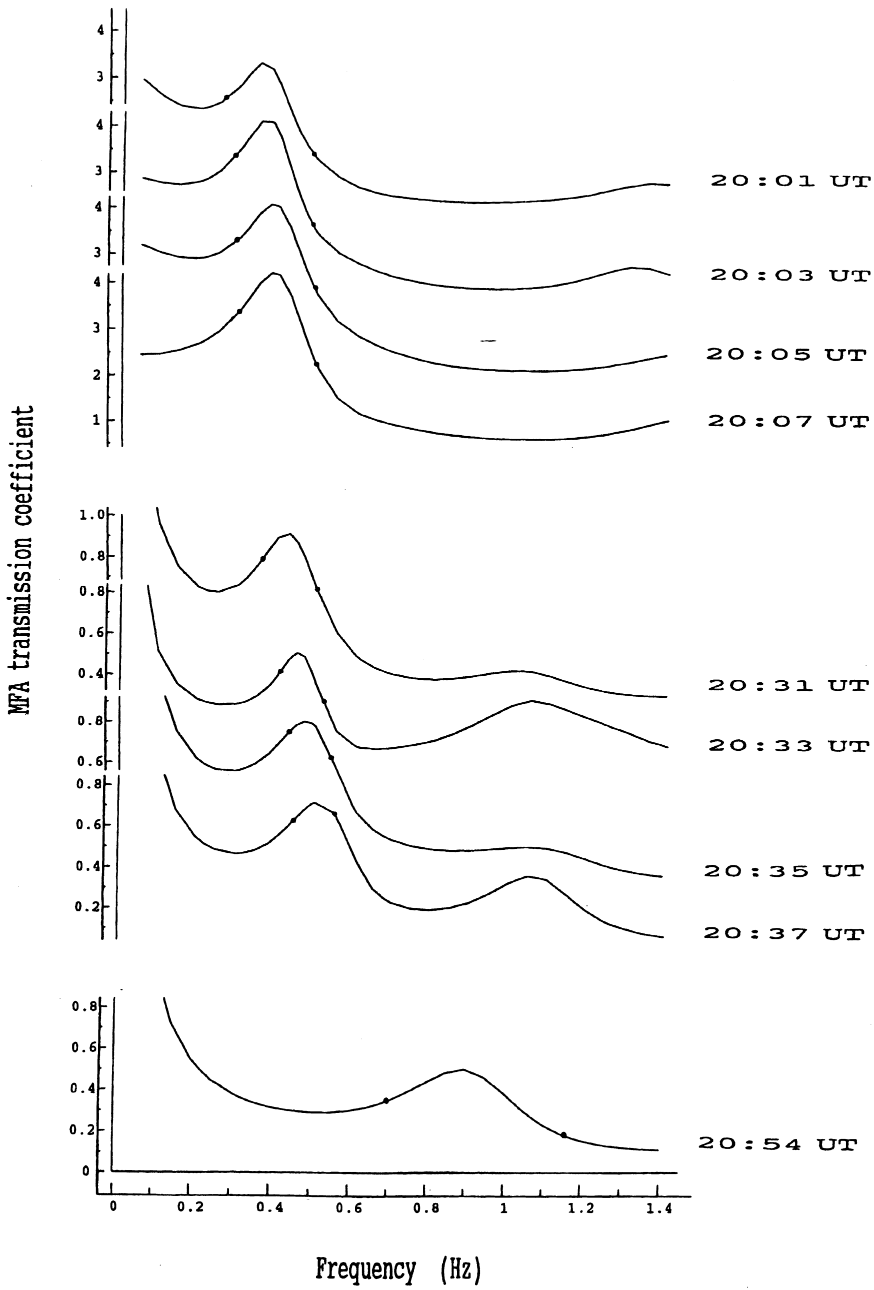

Fig. 4. Same as Fig. 3, but for the transmission coefficient. The wave band is constrained between the frequencies marked by dots on the curve.

If the BWP model was correct, the conditions in the two ionospheres at the opposite ends of the field line would have to be very similar so that the same frequencies would be reflected at both ends. This is hardly probable in general, or in the present case of solstice when one (southern) ionosphere is sunlit and the other not. Moreover, the existence of wave packet structure even during the IPDP phase would imply in the BWP model that the changes in the ionospheric conditions in the two hemispheres would have to be very similar and would have to occur at a very similar rate. Such uniformity is highly improbable.

Accordingly, the present results strongly require an alternative model of Pc1 pearl formation. One interesting model is the possibility of Pc1 wave growth modulation by the effect of simultaneous long-period ULF waves (Pc3–5 pulsations). Even rather small changes in relevant plasma variables (e.g., density) due to long-period waves are sufficient to cause large variations in EMIC wave growth in marginally stable plasmas at the equatorial growth region (Gail, 1990). The possibility of EMIC wave growth modulation by Pc3–5 pulsations has received increasing attention recently (see, e.g., Fraser et al., 1992; Rasinkangas et al., 1994; Plyasova-Bakounina et al., 1996; Mursula et al., 1999; Rasinkangas and Mursula, 1998).

We have studied the possible simultaneous existence of long-period waves using data from the IMAGE (earlier EISCAT) magnetometer network stations. During part of the Pc1 phase, strong Pc4–5 waves are observed at most stations of the network. Fig. 5 depicts the waveform and power spectrum of the X-component of Kautokeino station with a power maximum at about 5 mHz (period, T 200 s). This corresponds quite well to the simultaneous pearl repetition period during the Pc1 phase which is about 3 minutes. A detailed study of Fig. 1 shows that the repetition period is slightly shorter, about 2 minutes, during the IPDP phase. Because of the substorm expansion the IPDP phase is magnetically much more disturbed than the Pc1 phase, as seen in Fig. 6 which depicts the waveform and power spectrum at Kautokeino during this time. However, despite strong disturbances, Fig. 6 shows evidence for a subsidiary power maximum at about 7 mHz T 140 s) which corresponds fairly well to the pearl repetition period during the IPDP phase.

4.2. Consequences on IPDP formation

As discussed above, the pearl repetition period decreases from Pc1 phase to IPDP phase. In both models of Pc1 pearl formation (ULF modulation model and BWP model), an increase of wave frequency and a decrease of repetition period imply an inward movement of the wave source region to lower L-shells. Also, one can see in Fig. 1 that the relative intensity of waves at the different stations changes from the Pc1 phase to the IPDP phase. The amplitudes were roughly equally strong at Sodankylä and Oulu during the Pc1 phase but later, in the IPDP phase, clearly stronger at Oulu than at Sodankylä. Even at Nurmijärvi there were larger amplitudes during the IPDP phase than at Sodankylä. These facts give strong evidence for an inward movement of the wave source region after the substorm onset.

Several ground-based (Heacock, 1971b; Roth and Orr, 1975; Webster and Fraser, 1985) and satellite (Fraser et al., 1989; Erlandson et al., 1992; Mursula et al., 1994; Erlandson and Anderson, 1996) studies have shown that the source of Pc1 pearls is connected with the plasmapause. Therefore, the movement of the wave source to lower latitudes is probably also connected with the plasmapause moving to lower L-shells which is known to occur during high geomagnetic activity. The effect of the substorm is to move the resonant ion population to lower L-shells and to intensify this population, thereby increasing the EMIC growth rate at the lower L-shells, as observed in Fig. 1. The inward movement of the plasmapause is also in accordance with the observations (Kleimenova et al., 1995) that the ionospheric trough is found above the region of observation of an IPDP event.

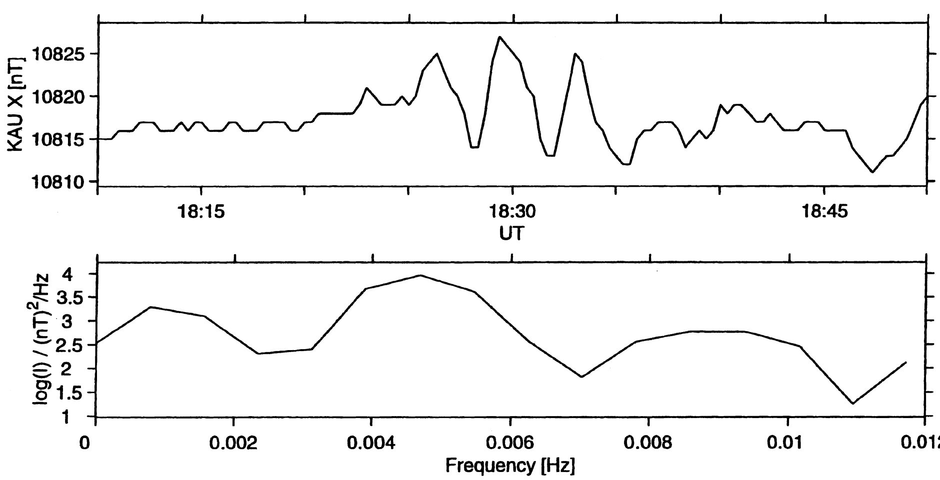

Fig. 5. The wave (top) and power spectrum of the X-component of Kautokeino station for part of the Pc1 phase of the event.

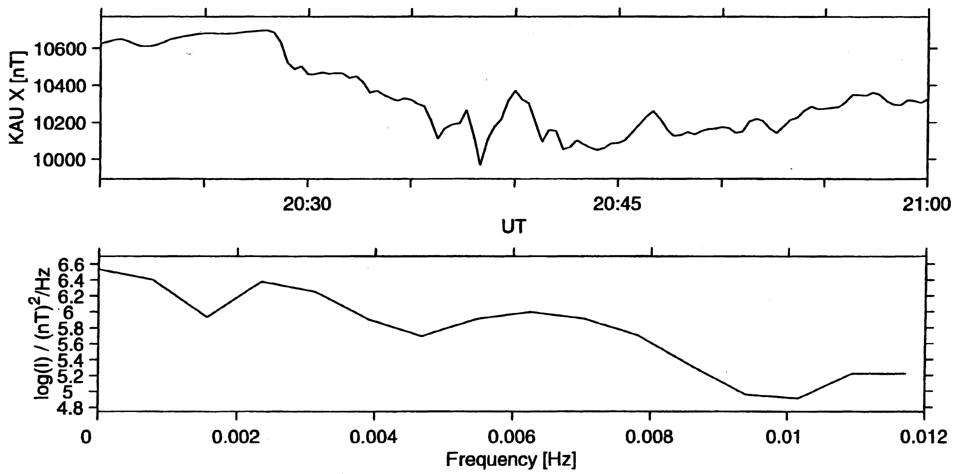

Fig. 6. The same as Fig. 5 around the IPDP phase.

Accordingly, significant changes in the magnetosphere are needed to explain the observations. In particular, these changes are necessary for the observed increase of the wave frequency in order to produce the IPDP signal. However, the magnetospheric changes alone are not sufficient for the observation of an IPDP signal on the ground. At and after substorm onset, the ionosphere is greatly disturbed by the increased precipitation of the new energetic charged particles entering the inner magnetosphere. These disturbances greatly modify the structure of the ionosphere over a large latitude (and longitude) range, as depicted in Fig. 2, and can lead to dramatic change of the reflection and transmission characteristics of the ionospheric Alfvén resonator for EMIC waves. As shown in Figs. 3 and 4, the model calculations of the ionospheric resonator consistently reproduce the wave frequency observed on the ground as the eigenmode of the resonator, even during the dramatically changing conditions after substorm onset. This suggests that the non-stationary ionospheric Alfvén resonator acts as an essential factor in the formation of the IPDP signal on the ground.

Accordingly, we propose a new, more complete model of IPDP formation in which the IPDP signal on the ground depends not only on magnetospheric changes but also on changes in the resonator conditions of the ionosphere. At any time, the magnetospheric Pc1 source supplies a range of wave frequencies, which can either be amplified or annihilated in the ionospheric resonator depending on the conditions of the ionosphere at the magnetospheric footpoint of the waves. When the wave source region moves to lower L-shells and increases its frequency, the ionosphere may or may not transmit the new frequencies to the ground. In the present model calculations we have verified that changes in the resonator conditions even in a stationary ionosphere can be sufficiently large to follow the increase of the wave frequency. However, such concomitant changes in the magnetosphere and ionosphere may not occur very often, despite the fact that the magnetospheric wave source may be extended in latitude and longitude and the waves may encounter ionospheres which may have somewhat different resonator conditions. Therefore, this model explains naturally why so few IPDPs, typically five per month, are seen on the ground, despite the ubiquitous occurrence of EMIC waves in the magnetosphere and the continuous substorm cycle with the related injections of new energetic charged particles.

5. Conclusions

We have calculated the response of the ionospheric resonator to an incident Alfvén wave using simultaneous observations of the EISCAT radar, and shown that the first minimum (or maximum) of the wave reflection (or transmission) coefficient corresponds well to the central wave frequency observed on the ground during the whole Pc1/IPDP event. This is in contradiction with the earlier view, which was based on the bouncing wave packet hypothesis, that the wave frequency on the ground corresponds to the maximum of the reflection coefficient. Accordingly, our result implies a need to revise the bouncing wave packet model of Pc1 pearls. We present evidence for the existence of long-period ULF waves with a period matching the simultaneous pearl repetition period, both during the Pc1 phase and the IPDP phase which have different pearl repetition periods. These observations support the alternative model of pearl formation according to which the ULF waves modulate the Pc1 growth rate at the equatorial source region. Moreover, we propose a new model of IPDP formation in which the IPDP signal on the ground depends not only on magnetospheric changes but also on changes in the resonator conditions of the ionosphere. This model naturally explains the rarity of IPDP events on the ground despite the ubiquitous occurrence of EMIC waves in the magnetosphere and the continuous substorm cycle. While the evidence presented in this paper is unique and conclusive, it is based on one event only, and needs to be supported by a statistically larger analysis which is already under way.

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