Geophysica (1987), Vol. 23, No. 1, pp. 1–19
Printed in Finland

550.388:523.982

STATISTICAL RESULTS OF IPDP PULSATIONS RECORDED IN FINLAND DURING 1975–1979

by

TAPANI PIKKARAINEN

Department of Physics, University of Oulu
SF–90570 Oulu, Finland

Abstract

We have analysed the IPDP magnetic pulsation events observed at the Finnish meridional chain of stations in 1975–1979. It has been shown that the mean value of their onset times is 17.20 hours in local time and they appear at Sodankylä when the *Kp* activity index is 3.6 on the average and at Nurmijärvi when it is 3.9. The end frequency of IPDP's is mainly between the He^+ and 0^+ gyrofrequencies on the corresponding field line in the equatorial plane. Our data shows that the rate of the upward sweep of the pulsation frequency in IPDP increases with increasing magnetic activity. If we take into account the variability of the solar activity most of the IPDP's occur in 1976–1977, *i.e.* in years of low solar activity but they are infrequent in 1979. Both the end frequency and slope of IPDP's decreases by 1979. We conclude that these long-term variations are due to the changes in heavy ion populations which effect on the growth rate and propagation of ion cyclotron waves in the magnetosphere. Such variations complicate the interpretation of the upward sweep of the pulsation frequency in IPDP.

1. *Introduction*

Geomagnetic pulsations, also called ULF (ultra low frequency) waves, correspond to the lowest frequency range (0–10 Hz) in the electromagnetic spectrum. They can be divided into two main categories: those of a regular and mainly continuous (*Pc*) character, and those with an irregular (*Pi*) pattern. Both of these categories are divided into several subgroups (see JACOBS *et al.*, 1964).

Several types of magnetic pulsations in the high-end of the ULF spectrum occur during auroral disturbances or substorms (KANGAS *et al.*, 1984). A *PiB* (*Pi* burst) event appears at the onset of the substorm around the midnight sector. This burst with a wide frequency range lasts only for some minutes and it is often followed by an IPDP (intervals of pulsations of diminishing periods) event on the evening side of the auroral zone and by a *PiC* (*Pi* continuous) event on the morning side. *PiC* pulsations represent broad-band, long-lasting *Pi* events. IPDP pulsations (first reported by TROITSKAYA and MELNIKOVA, 1959) are characterized by a continuously increasing frequency from about 0.1 Hz to 2 Hz in 0.2 – 2 h. Examples of different pulsation events are shown *e.g.* by HEACOCK (1967 a,b), KANGAS *et al.*,(1979, 1984) and PIKKARAINEN *et al.* (1983).

An IPDP is a well-defined signature of a magnetospheric substorm and it is easily identified in pulsation recordings. For many years a north-south network of induction coil magnetometers has been operated in Finland. It has been applied in several studies where the meridional profile of the wave field has been needed (see *e.g.* LUKKARI *et al.*, 1977, KANGAS *et al.*, 1979, BARANSKY *et al.*, 1981, BÖSINGER *et al.*, 1981, MALTSEVA *et al.*, 1981, PIKKARAINEN *et al.*, 1983, 1986).

It is the aim of the present work to make a statistical study of some IPDP characteristics on the basis of the continuous data collected in Finland, especially during IMS (International Magnetospheric Study, 1976–79) to confirm statistically some of the main results of previous studies using our unique data sets. Special emphasis has been given to search for trends related to the solar cycle.

2. *Ion cyclotron instability and heavy ions*

It is generally accepted that IPDP pulsations are generated via the ion cyclotron resonance mechanism where energy is transferred to the waves from the westward drifting hot particles injected into the magnetosphere during the substorms (TROITSKAYA, 1961, HEACOCK, 1967a, GENDRIN, 1970). The ion cyclotron instability occurs when the Doppler shifted wave frequency is equal to the local cyclotron frequency. Pulsations are amplified when the electric and magnetic vectors of the wave rotate in the same sense as the particles with angular frequency equal to the cyclotron frequency of the particles. In the limit of linear theory the growth rate of the ion cyclotron instability is

$$\gamma = \frac{\pi \eta \Omega^2}{(n_w + n_c)\, 2\omega} \left(1 - \frac{\omega}{\Omega}\right)^2 \frac{A - (\omega/\Omega)/(1 - \omega/\Omega)}{1 - \omega/2\Omega} \tag{1}$$

as given by KENNEL and PETSCHEK (1966) and LIN and PARKS (1974, 1976). n_w and n_c are densities of warm and cold particles, η is the number density of resonant particles, ω is the wave frequency and Ω is the local ion cyclotron frequency. The anisotropy A is determined by the equation

$$A = (T_{\perp}/T_{\parallel}) - 1 \tag{2}$$

where $T_{\perp}$ and $T_{\parallel}$ are distribution temperatures perpendicular to an external magnetic field $\bar{B}_0$ and parallel to $\bar{B}_0$, respectively. In the proton plasma these waves are left-hand polarized and all frequencies below the equatorial proton gyrofrequency can travel to the ground along magnetic field lines.

Recent satellite observations have shown that the presence of heavy ions (He^+ and 0^+) even in small quantities in cold plasma can has a profound effect on the generation and propagation of ion cyclotron waves (Young *et al.*, 1981, Roux *et al.*, 1982). Heavy ions can alter the frequencies at which wave growth occurs as well as the growth rates themselves. Also both polarization and dispersion characteristics are different in the multicomponent plasma from those in the proton plasma.

The effective amplification of waves in the magnetosphere depends also on the amount of time spent travelling through the growth region. Therefore the more relevant quantity for wave amplification is the so called convective growth rate which is the ratio between the temporal growth rate and the group velocity. Comberoff and Niera (1983) have calculated the convective growth rate of ion cyclotron waves in the presence of two or three cold components. They show that amplification is the result of an interplay between the cold species and the thermal anisotropy of the energetic protons.

Kozyra *et al.* (1984) extend their calculations to the plasma considering multiple ions in the energetic anisotropic component as well as in the cold component. They give the following formula for the convective growth rate:

$$S = \left\{ \sum_l \frac{\eta_{lw}\sqrt{\pi}}{M_l^2 \alpha_{\parallel,l}} \left[(A_l + 1)(1 - M_l X) - 1\right] \cdot \exp\left[\frac{-\eta_{lw}}{M_l} \frac{(M_l X - 1)^2}{\beta_{lw} X^2}\right] \Bigg/ \left[\frac{(1-\delta)}{(1-X)} + \right.\right.$$
$$\left.\left. + \sum_j \frac{(\eta_{jw} + \eta_{jc}) M_j}{1 - M_j X}\right]\right\} \cdot \left\{2X^2 \left[\frac{(1-\delta)}{(1-X)} + \sum_i (\eta_{iw} + \eta_{ic}) \frac{M_i}{1 - M_i X}\right]\right\}^{-1} \tag{3}$$

where the summations over l include all ions and those over i and j include only ions heavier than H^+. $\alpha_{\parallel,l}$ is the parallel thermal velocity of energetic species, $X = \omega_r/\Omega_p$ is the normalized wave frequency with respect to the proton gyrofrequency, $\beta_{lw} = 8\pi\eta_{lw} k_B T_{\parallel,l} B_0^2$, η_{lw} is the density of the warm component of species l, k_B is Boltzman's constant, $\delta = \omega_{ppc}^2/\omega_{ppw}^2$, $\omega_{ppw(c)}$ is the plasma frequency of warm (cold) components, $\eta_{jw(c)} = M_j(\omega^2_{pjw(c)}/\omega^2_{ppw})$ and $M_j = m_j/z_j m_p$.

Model calculations by KOZYRA *et al.* (1984) show four major effects on the growth and propagation characteristics of waves which are due to the inclusion of heavy ions in the energetic component of the magnetospheric plasma which they summarize as follows:

1) Some wave growth occurs at low frequencies below the corresponding marginally unstable wave mode for each heavy ion.
2) Enhanced quasi-monochromatic peaks in the growth rate appear just below the 0^+ and He^+ gyrofrequency.
3) Stop bands, decreased group velocity and other effects normally attributed to cold heavy ions can be produced or enhanced by energetic heavy ions.
4) Energetic ions can suppress the wave growth either partially or completely at frequencies above the marginally unstable wave modes.

Besides the effects on the growth rate, heavy ions change the propagation characteristics of ion cyclotron waves. PERRAUT (1982) has shown by simultaneous observations made on the GEOS satellites and on the ground that low-frequency (below the He^+ gyrofrequency) ion cyclotron waves usually reach the ground while high-frequency (above the He^+ gyrofrequency) waves do not. This is simply due to the fact that when He^+ is present high-frequency waves are reflected at a latitude $\phi_m = 10^\circ - 20^\circ$ (MAUK, 1982, RAUCH and ROUX, 1982). However, if the abundance of He^+ ions is small enough, waves can tunnel through the stop zone (PERRAUT *et al.*, 1984). FRASER and MCPHERRON (1982) report ATS-6 observations which show that 0^+ ions introduce similar effects as He^+.

Several theories have been introduced to explain the rising midfrequency characteristics of IPDP event. We shortly present most of them as follows.

1) Energetic plasma drifting inward on the afternoon-evening side of the magnetosphere produces progressively higher pulsation frequencies as the plasma drifts to smaller L-shells (GENDRIN *et al.*, 1967, TROITSKAYA *et al.*, 1968).
2) Plasma, impulsively injected near midnight will result in protons drifting differentially into the evening-afternoon sector. The higher energies arrive first over a given recording site, exiting lower IPDP frequencies in accordance with $f \sim E^{-1/2}$ (FUKUNISHI, 1969, 1973, MALTSEVA *et al.*, 1970).
3) An increase of the magnetic field in the equatorial source region causes an increase in the ion-cyclotron wave frequency (ROXBURGH, 1970).
4) The frequency dispersive effect of IPDP events can be produced by either spatial or temporal changes in the cold plasma density n_c (LIN and PARKS, 1976). The effects of changing n_c can be very important near the plasmapause

where one frequently detects detached plasma regions (CHAPPELL, 1974).

5) Hot protons injected at substorm onset drift around to the dusk sector where they encounter cold plasma and become cyclotron unstable. As protons arrive later at lower L shells the source moves inwards and the frequency increases (SØRAAS *et al.*, 1980, MALTSEVA *et al.*, 1981).
6) The presence of helium ions in the plasmasphere enhances the velocity dispersion of the unstable waves, which leads to the variation in the transit time of the unstable waves. This can be seen as the frequency increase in the IPDP events observed on the ground (LEE and KWOK, 1984).

It is most probable that a superposition of several of those mechanisms must usually be taken into account in search for an explanation to the observed effects (see KANGAS *et al.*, 1974 and HEACOCK *et al.*, 1976). Observations show that the source of IPDP pulsations moves both westwards (FUKUNISHI, 1969, MALTSEVA *et al.*, 1970, GULELMI, 1974, FRASER and WAWRZYNIAK, 1978, PIKKARAINEN *et al.*, 1983) and radially inwards (HEACOCK *et al.*, 1976, FRASER and WAWRZYNIAK, 1978, MALTSEVA *et al.*, 1981).

3. *Experimental*

Most of the data in the present study comes from five magnetic pulsation stations and seven riometers forming a north-south chain from L = 6.0 to L = 3.3 in Finland. Locations of the stations are given in Table 1.

Magnetic pulsations have been recorded by induction coil magnetometers, which are most sensitive in the frequency range from 0.1 Hz to a few Hz. The antenna pattern of 27.6 MHz riometers projected to the level of 100 km in the ionosphere is about 200 km in the east-west extent and about 90 km in north-south extent.

Table 1. Locations of Finnish riometer and pulsation magnetometer stations.

Station	Geogr. coordinates		L-value	Riometer	Pulsation magnetometer
	Latitude	Longitude			
Kevo	69.8	27.0	6.0	x	x
Ivalo	68.6	27.5	5.5	x	
Sodankylä	67.4	26.6	5.1	x	x
Rovaniemi	66.6	25.8	4.8	x	
Oulu	65.1	25.5	4.3	x	x
Jyväskylä	64.2	25.7	3.7	x	x
Nurmijärvi	60.5	24.7	3.3	x	x

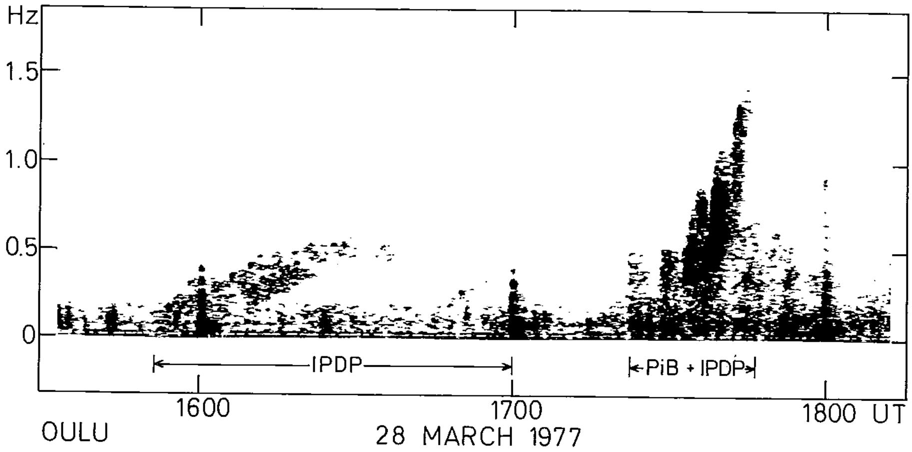

Fig. 1. Dynamic spectrum of two IPDP events observed at Oulu (L = 4.3) on March 28, 1977.

The registration speed of both pulsation magnetometers and riometers allows one minute time resolution.

Almost continuous data are available from the years 1975–79. However, the quality of data from Jyväskylä has often been poor and mostly been excluded. Data gaps also occur at other stations, especially at Kevo. In any case, the data allow a unique study of the meridional profiles of IPDP characteristics from the auroral latitudes to mid-latitudes.

IPDP events have been analysed mainly by sonagraph. Dynamic spectra are useful to identify the events and to determine their characteristics. A good example is shown in Fig. 1. It is important to notice that the term 'IPDP' was originally adopted to signify a series of pulsation events with an upward sweep of pulsation frequency (TROITSKAYA and MELNIKOVA, 1959). Later the same term has been adopted also for single events.

4. *IPDP characteristics in relation to local time, magnetic activity and latitude*

To summarize the results of previous studies, we have collected statistical results of IPDP characteristics from the following papers: KNAFLICH and KENNEY (1967), FUKUNISHI (1969), GENDRIN (1970), HEACOCK (1971), SØRAAS *et al.*, (1980), FUKUNISHI *et al.* (1981), LOPEZ (1982) and PIKKARAINEN *et al.*, (1983). Data sets of these studies are from different periods in 1965–1981 covering the L-values from 6.1 to 2.8.

1) Most of IPDP events occur between 15–21 LT.
2) The IPDP's appear most clearly at sites in the 60–65° geomagnetic latitude range.
3) With increasing *Kp*-index IPDP's are displaced towards earlier local times and lower latitudes.
4) The maximum occurrence of IPDP's moves to a later local time when the L-value decreases.
5) IPDP events have higher end frequencies and steeper slopes at the low-latitude station than at the high-latitude one.

We repeat some of these studies with our meridional data. In Fig. 2 the occurrence of 174 IPDP events in local time recorded at Sodankylä in 1975–79 are shown for different *Kp* values. Most of the IPDP events occur at 15–20 LT when $Kp = 3$. A tendency for a shift to an earlier local time can be noted with increasing *Kp*. The average onset time of analysed IPDP's is 15.40 UT at Sodankylä, 15.50 UT at Oulu (128 events) and 16.10 UT at Nurmijärvi (118 events). If we take into account the geographical longitude of these stations (see Table 1) we may conclude that the mean onset time of the IPDP at the Finnish meridian is 17.20 hours in local time at auroral latitudes and a little later at lower latitudes.

In Fig. 3 we show the number of IPDP's at Sodankylä as a function of the

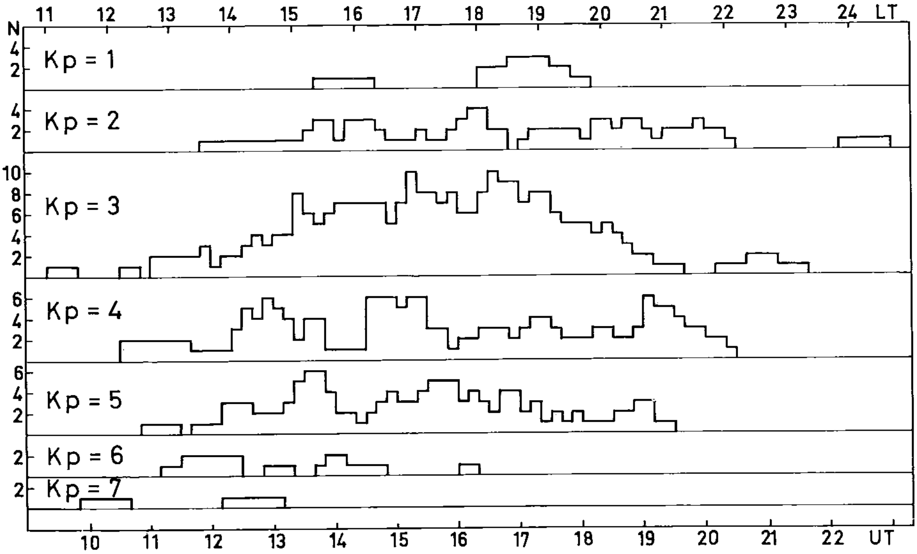

Fig. 2. Universal time distribution of IPDP occurrences at Sodankylä in 1975–1979 for different *Kp* values. Local time is approximately UT + 1 h 40 min.

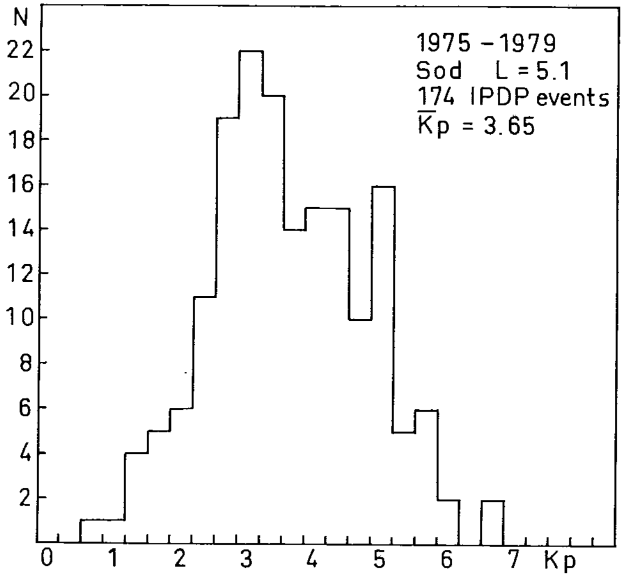

Fig. 3. Number of IPDP occurrences at Sodankylä as a function of magnetic activity measured by the *Kp* index.

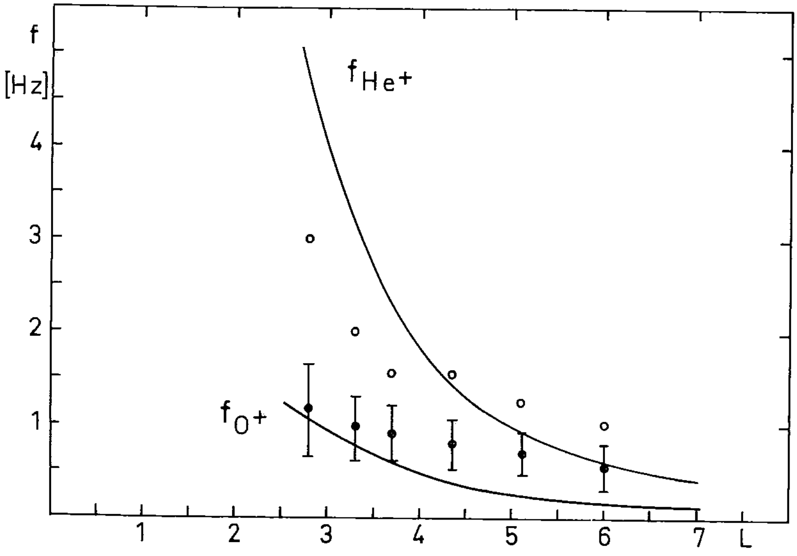

Fig. 4. The maximum (o) and mean (•) end frequency of IPDP's at Kevo (L = 6.0), Sodankylä (L = 5.1), Oulu (L = 4.3), Jyväskylä (L = 3.7), Nurmijärvi (L = 3.3) and Borok (L = 2.8). The standard deviation is also shown. Solid lines give the He^+ and 0^+ gyrofrequencies in the equatorial plane as the function of L.

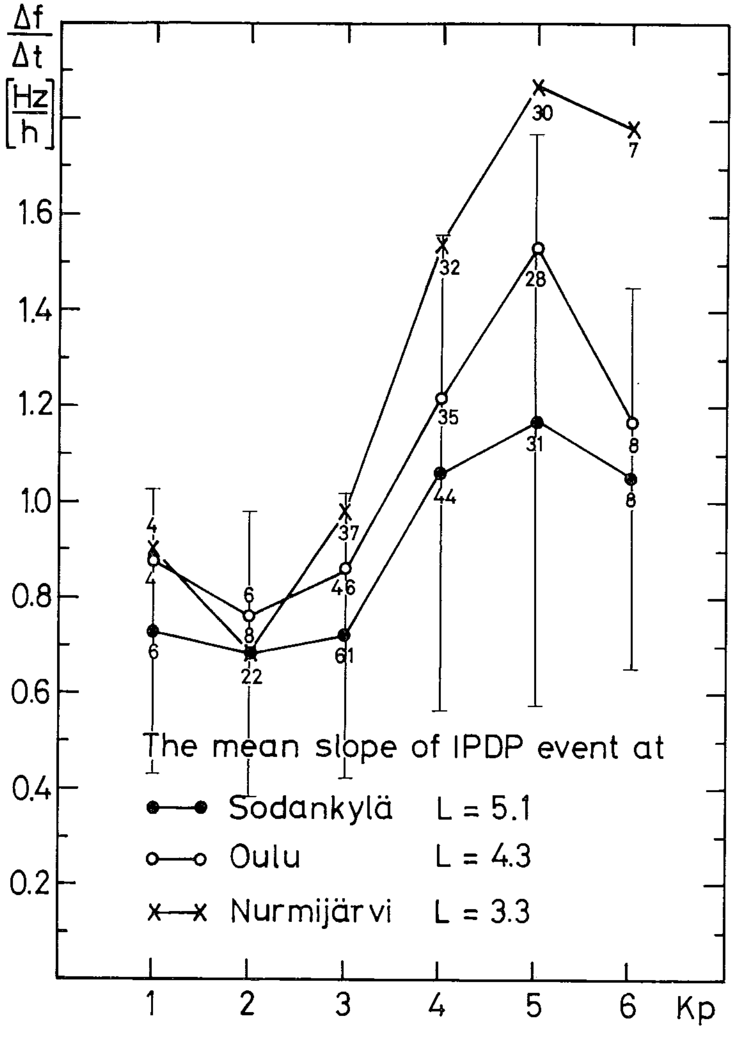

Fig. 5. The mean slope of IPDP events observed at Sodankylä, Oulu and Nurmijärvi in 1975–1979 for different *Kp* values. The standard deviation is shown for Sodankylä data. Number of events for the given *Kp* is indicated.

Kp-index. The mean *Kp* value is 3.6 at Sodankylä, 3.8 at Oulu and 3.9 at Nurmijärvi showing a tendency of increasing magnetic activity towards lower latitudes. Conclusions from Figs. 2 and 3 are basicly the same as the ones cited above in 1–4.

Pikkarainen *et al.* (1983) showed in their Fig. 5 that the end frequency of

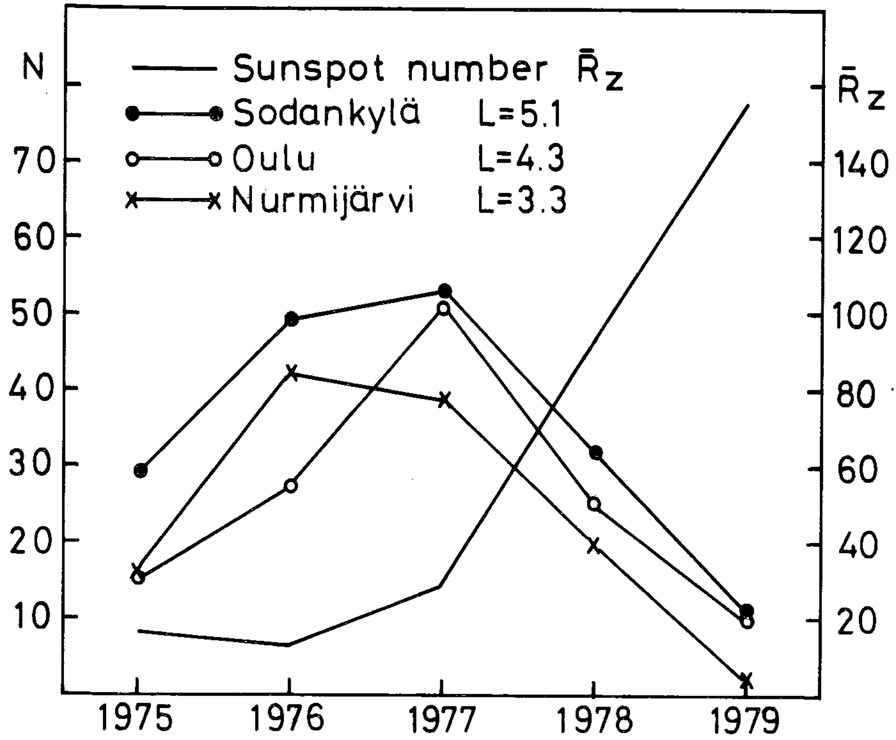

Fig. 6. Number of IPDP occurrences at the Finnish chain of pulsation magnetometers in years 1975–1979. The annual mean sunspot number $\bar{R}_z$ is shown to represent the solar activity.

IPDP pulsations is typically lower than the He^+ gyrofrequency at the corresponding field line in the equatorial plane. In Fig. 4 we repeat the results presented by Pikkarainen *et al.* (1983) but with inclusion of those from all Finnish stations. The end frequencies are mainly between He^+ and 0^+ gyrofrequencies. This observation shows that the end frequency of IPDP's depends on the L value. It also shows that heavy ions in the magnetosphere control the frequency band of pulsations recorded on the ground as expected on the basis of the theory.

Pikkarainen *et al.* (1983) made an analysis of the slope of IPDP events measured at Borok (L = 2.8) and at Lovosero (L = 5.1). The slope was distinctly greater at Borok than at Lovosero, especially during high magnetic activity. Corresponding results from Sodankylä, Oulu and Nurmijärvi are shown in Fig. 5. The slope becomes much steeper with increasing magnetic activity at all stations. The slope does not depend on latitude for low *Kp*-values whereas during more active periods it becomes progressively steeper further south from the auroral zone.

It is remarkable that the slope at Lovosero shown by Pikkarainen *et al.* (1983) in their Fig. 6 does not depend in any important way on the level of magnetic activity which result differs much from that shown in Fig. 5 for Sodankylä. This difference is very probably due to the fact that Pikkarainen *et al.* (1983) separated in their analysis the IPDP events recorded only at Borok and only at Lovosero. Thus in Lovosero data there is no contribution from low-latitude events.

5. *Electron precipitation associated with IPDP's*

Thorne and Kennel (1971), Thorne (1974) and Thorne and Larsen (1976) have suggested that relativistic electrons may be precipitated from the magnetosphere by electromagnetic ion cyclotron waves via parasitic interaction. On the basis of this theory an increase in electron precipitation into the atmosphere might occur during IPDP's. We have searched for such an evidence by combining magnetic pulsation and riometer data from the north-south net of stations in Finland (Lukkari *et al.*, 1977, Pikkarainen *et al.*, 1986). It is shown that there is a certain type of riometer absorption event which can be associated with IPDP's. It has also been shown that the electron precipitation region moves southwards as the IPDP frequency increases.

In the present study we estimate with an improved statistics how often riometer absorption is associated with IPDP's. We have analysed riometer data for the 196 IPDP events observed at Sodankylä, Oulu and Nurmijärvi. In 165 cases riometer absorption was recorded at least at one station. A more detailed description of this association is shown in Table 2.

Table 2. Number of cosmic noise absorption (CNA) events observed at the Finnish chain of riometers during the 196 IPDP events recorded in 1975–1979. The number of occurrence and maximum absorption at Kevo (K), Ivalo (I), Sodankylä (S), Rovaniemi (R), Oulu (O), Jyväskylä (J) and Nurmijärvi (N) are also given.

Year	Number of CNA	Occurrence of CNA							Maximum absorption						
		K	I	S	R	O	J	N	K	I	S	R	O	J	N
1975	30	13	21	26	26	24	11	2	2	2	5	9	9	2	1
1976	43	15	30	30	27	20	7	0	2	10	8	12	9	2	0
1977	54	32	34	42	34	24	5	1	11	14	6	10	12	0	1
1978	27	15	17	18	13	7	6	2	9	7	0	4	3	3	1
1979	11	5	7	8	8	3	0	0	3	1	2	3	2	0	0
75–79	165	80	109	124	108	78	29	5	27	34	21	38	35	7	3

Our data analysis shows that electron precipitation activity around the IPDP lasts longer than the IPDP itself. If the typical duration of IPDP events is 41 min the corresponding figure for CNA is 75 min. It is interesting to note that although riometer absorption has most often been measured at Sodankylä the maximum absorption more probably occurs either to the north or south from Sodankylä. This is a further evidence for the observation made by RANTA *et al.* (1983) that the electron precipitation region expands westwards after the onset of the substorm along two separate zones.

It is interesting to study what is the association between electron precipitation and magnetic pulsation events in the afternoon-to-evening sector in general. We have looked into this problem more extensively by making use of a list of absorption events observed in Finland in this local time sector (RANTA and RANTA, 1979). 146 time intervals with riometer absorption have been reported in 1976–78. In 29 cases (20 %) IPDP pulsations were present, in 29 (20 %) cases PiC pulsations, in 15 cases (10 %) PiB pulsations, in 35 cases (24 %) Pc 1 pulsations and in 38 cases (26 %) no short-period magnetic pulsations could be identified.

We conclude that electron precipitation is associated with IPDP pulsations with a high probability. ARNOLDY *et al.* (1979) arrive at a similar conclusion. Recently IMHOF *et al.* (1986) reported satellite observations of simultaneous relativistic electron and energetic ion precipitation spikes near the plasmapause. Although all these measurements are in favour of the precipitation mechanism suggested by THORNE and KENNEL (1971) further clarification is needed. In particular, we need more information about the energy spectrum of precipitating electrons during IPDP's.

6. *IPDP's and solar activity cycle*

It is known that the occurrence frequency of Pc 1 magnetic pulsations is anticorrelated with the relative sunspot number (FRASER-SMITH, 1970, 1981, MATVEYEVA *et al.*, 1972, KAWAMURA *et al.*, 1983). The corresponding analysis of IPDP's has been done only recently by MALTSEVA *et al.*, (1986) where IPDP data collected independently in U.S.S.R., Finland and Alaska were combined. This analysis shows that IPDP events recorded on the ground are more numerous in the years of low solar activity than during enhanced solar activity. In the present study, we are able to extend the data presentation as given by MALTSEVA *et al.*, (1986) in certain important respects.

In Table 3 and in Fig. 6 we show the number of IPDP's measured at Sodankylä, Oulu and Nurmijärvi in the years 1975–79 together with the mean sunspot

Table 3. Occurrence and mean slope [*Hz/h*] of IPDP events in years 1975–1979 recorded by the Finnish chain of pulsation magnetometers. $\bar{R}_z$ is the annual mean of the relative sunspot number.

	Kev L = 6.0		Sod L = 5.1		Oul L = 4.3		Nur L = 3.3		
Year	N	$\Delta f/\Delta t$	N	$\Delta f/\Delta t$	N	$\Delta f/\Delta t$	N	$\Delta f/\Delta t$	$\bar{R}_z$
1975			29	1.02	15	1.50	16	1.69	16
1976	12	0.79	49	0.94	27	1.25	42	1.35	13
1977	12	0.89	53	0.93	51	1.12	39	1.42	28
1978	3	0.31	32	0.70	25	0.91	20	1.23	93
1979	3	0.36	11	0.62	10	0.63	2	0.53	155
75–79	30	0.74	174	0.89	128	1.12	119	1.38	61

number $\bar{R}_z$. The solar cycle No. 21 started in June, 1976. Even if the data sample is still limited and it is not possible to come to any unambiguous conclusions one notes, however, that most of the IPDP's has been measured in the years 1976–77 before the rapid rise of the solar activity. It is also significant that the number of events is definitely very low in 1979 when the solar cycle approaches its maximum phase.

We have also searched for any long-term variation in other IPDP characteristics. The highest end frequency of IPDP's is given in Table 4 and Fig. 7 shows the trends of the IPDP slope in 1975–79. The end frequency has been 0.8 Hz or smaller at all Finnish stations in 1979 (active year) whereas in 1975–76 (quiet years) it is above 1.2 Hz except at Kevo. The slope in *Hz/h* is also smaller in 1979 than in the years of low solar activity although the variability of values is great.

It is our conclusion that the occurrence frequency and some characteristics of IPDP's depend on solar activity cycle of 11 years. As the same tendency is known for *Pc* 1 pulsations as mentioned before, it is useful to make a more detailed

Table 4. The highest frequency in IPDP event recorded at five Finnish stations in years 1975–1979.

	The highest end frequency in IPDP's in Hz					
Year	Kev	Sod	Oul	Jyv	Nur	$\bar{R}_z$
1975		1.40	1.50		1.80	16
1976	0.90	1.20	1.40	1.50	1.55	13
1977	1.20	1.35	1.40	1.40	2.00	28
1978	0.40	1.05	1.25	1.30	1.65	93
1979	0.60	0.80	0.80	0.70	0.70	155

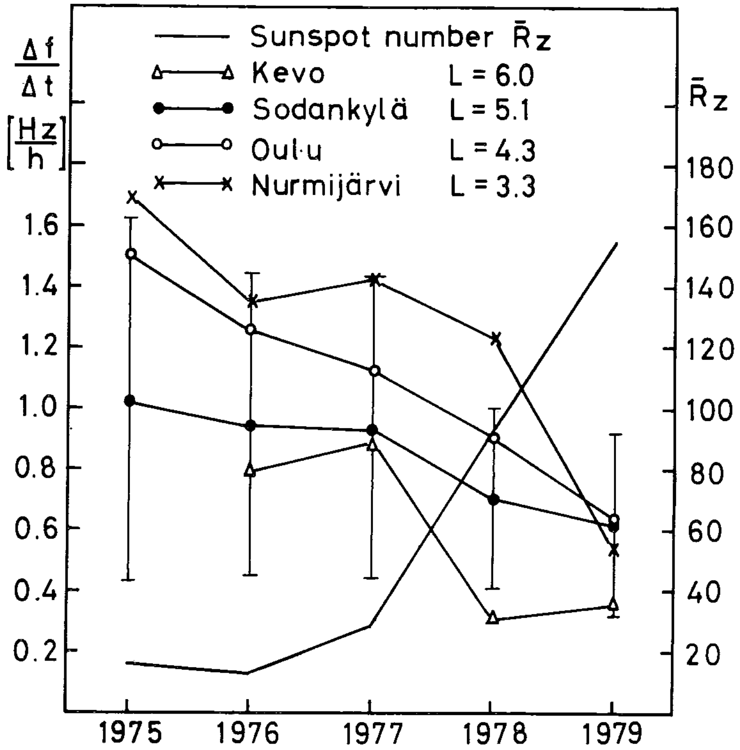

Fig. 7. Mean rate of the upward sweep of pulsation frequency in years 1975–1979 as deduced from Finnish pulsation magnetometer data. The standard deviation is shown for Sodankylä data.

reference to such studies. It has been suggested (see *e.g.* KAWAMURA *et al.*, 1983) that the inverse relation between the *Pc* 1 occurrence frequency and sunspot cycle is due to intense attenuation of waves in the disturbed ionospheric duct and compression of the plasmasphere in active years.

If we apply the same interpretation to IPDP's at least two consequencies can be noted (see HEACOCK *et al.*, 1976):

1) High frequencies should be more characteristic for IPDP's in active years when the plasmapause is statistically at lower latutude.
2) The IPDP slope should be greater in active years as the steepness of the plasmapause is greater as it is far in.

As shown before our data do not support these expectations. It is also remarkable that KAWAMURA *et al.* (1983) report the lack of high-frequency *Pc* 1 pulsations in active years.

A new interpretation is possible according the general theory of ion-cyclotron waves forwarded by KOSYRA *et al.* (1984). They conclude that an increase of energetic heavy ions in the magnetosphere effectively suppress the wave growth at frequencies above the marginally unstable wave modes. According to GEOS satellite measurements reported by YOUNG *et al.* (1982) the density of energetic 0^+ ions has been about ten times higher in November 1979 than in May 1977. We believe that such an increase of heavy ions must heavily limit the frequency band of emissions to be seen on the ground which could explain our IPDP observations in these years.

7. *Discussion*

In this review we have shortly described generation and propagation mechanisms of magnetospheric ion cyclotron waves. Especially we have drawn attention to effects of heavy ions. The most important result is the solar cycle variation in IPDP occurrences. We have shown that IPDP plasma wave events are less frequent and their characteristics are different in the years of high sunspot activity than in years of low activity. We suggest that this observation is indicative of a major effect of heavy ions, including both cold and energetic components on the wave growth and propagation of ULF ion cyclotron waves in the magnetosphere. The most prominent effect seems to be due to 0^+ ions which are known to be well correlated with both magnetic and solar activity (YOUNG *et al.*, 1982).

It is evident from above that due to the varying effect of heavy ions on ion cyclotron waves it is difficult to make any definite conclusion about the IPDP mechanism without having sufficient information about plasma populations. As mentioned before both the azimuthal and radial movement of the IPDP source occurs. The radial drift seems to be intensified during more active periods as indicated by the increase of the slope during high *Kp*'s. This may be interpreted as an increase of the $\bar{E}$ x $\bar{B}$ drift.

If we combine the present results on the relationship of the IPDP slope to magnetic activity to those presented previously by PIKKARAINEN *et al.* (1983) we may conclude that steep slopes are typical at low latitudes during high magnetic activity. Such a behaviour might be explained in terms of variations in plasma density in the plasmapause region. As was mentioned before the plasmapause is further in and the plasma density gradient at the plasmapause is steeper during high magnetic activity.

We conclude that both the radial movement of the IPDP source and the changes of cold plasma density in the plasmapause region can explain the present statistical results. In order to make more definite conclusions measurements of plasma populations and electric fields in the magnetosphere are needed.

Acknowledgements: The author is grateful to H. Ranta, Geophysical Observatory, Sodankylä, for riometer data used in the present study and N. Maltseva, Institute of Physics of the Earth, Moscow, for valuable discussions and suggestions. I also thank P. Tanskanen, Department of Physics, University of Oulu, for his careful reading of the manuscript. In particular I express my thanks to J. Kangas, Department of Physics, University of Oulu, for his continue support and excellent advices during this work.

REFERENCES

ARNOLDY, R.L., LEWIS, Jr., P.B., and L.J. CAHILL, Jr., 1979: Polarization of *Pc*1 and IPDP pulsations correlated with particle precipitation. *J. Geophys. Res.*, 84, 7091–7098.

BARANSKY, L., GOLIKOV, Yu., FEYGIN, F., HARCHENKO, I., KANGAS, J., and T. PIKKARAINEN, 1981: Role of the plasmapause and ionosphere in the generation and propagation of pearl pulsations. *J. Atmos. Terr. Phys.*, 43, 875–881.

BÖSINGER, T., ALANKO, K., KANGAS, J., OPGENOORTH, H., and W. BAUMJOHANN, 1981: Correlations between PiB type magnetic micropulsations, auroras and equivalent current structures during two isolated substorms. *Ibid.*, 43, 933–945.

CHAPPELL, C.R., 1974: Detached plasma regions in the magnetosphere. *J. Geophys. Res.*, 79, 1861–1870.

COMBEROFF, L., and R. NIERA, 1983: Convective growth rate of ion cyclotron waves in a H^+-He^+ and $H^+-He^+-0^+$ plasma. *Ibid.*, 88, 2170–2174.

FRASER, B.J., and S. WAWRZYNIAK, 1978: Source movements associated with IPDP pulsations. *J. Atmos. Terr. Phys.*, 40, 1281–1288.

–»– , and R.L. McPHERRON, 1982: *Pc*1-2 magnetic pulsation spectra and heavy ion effects at synchronous orbit: ATS 6 results. *J. Geophys. Res.*, 87, 4560–4566.

FRASER-SMITH, A.C., 1970: Some statistics on *Pc*1 geomagnetic micropulsation occurrence at middle latitudes: Inverse relation with sunspot cycle and semi-annual period. *Planet. Space Sci.*, 75, 4735–4745.

–»– , 1981: Long-term predictions of *Pc*1 geomagnetic pulsations: Comparison with observations. *Ibid.*, 29, 715–719.

FUKUNISHI, H., 1969: Occurrence of sweepers in the evening sector following the onset of magnetospheric substorms. *Rep. Ionos. Space Res. Jpn.*, 23, 21–34.

–»– , 1973: Occurrence of IPDP events accompanied by cosmic noise absorption in the course of proton aurora substorms. *J. Geophys. Res.*, 78, 3981–3986.

–»– , TOYA, T., KOIKE, K., KUWASHIMA, M., and M. KAWAMURA, 1981: Classification of hydromagnetic emissions based on frequency-time spectra. *Ibid.*, 86, 9029–9039.

GENDRIN, R., 1970: Substorm aspects of magnetic pulsations. *Space Sci. Rev.*, 11, 54–130.

–»– , LACOURLY, S., TROITSKAYA, V., GOKHBERG, M., and R.V. SCHEPETNOV, 1967: Caracteristiques des pulsations irregulieres de periode decroissante (IPDP) et leuers relations avec les variations du flux des particules piegèes dans la magnetosphere. *Planet. Space Sci.*, 15, 1239–1259.

GULELMI, A.V., 1974: Diagnostics of the magnetosphere and interplanetary medium by means of pulsations. *Space Sci. Rev.*, 16, 331–345.

HEACOCK, R.R., 1967a: Evening micropulsation events with a rising midfrequency characteristic. *J. Geophys. Res.*, 72, 399–408.

–»– , 1967b: Two subtypes of type *Pi* micropulsations. *Ibid.*, 72, 3905–3917.

–»– , 1971: Spatial and temporal relations between *Pi* bursts and IPDP micropulsation events. *Ibid.*, 76, 4494–4504.

–»– , HENDERSON, D.J., REID, J.S., and M. KIVINEN, 1976: Type IPDP pulsation events in the late evening-midnight sector. *Ibid.*, 81, 273–280.

IMHOF, W.L., VOSS, H.D., REAGAN, J.B., DATLOWE, D.W., GAINES, E.E., and J. MOBILIA, 1986: Relativistic electron and energetic ion precipitation spikes near the plasmapause. *Ibid.*, 91, 3077–3088.

JACOBS, J.A., KATO, Y., MATSUSHITA, S., and V.A. TROITSKAYA, 1964: Classification of geomagnetic micropulsations. *Ibid.*, 69, 180–181.

KANGAS, J., LUKKARI, L., and R.R. HEACOCK, 1974: On the westward expansion of substorm-correlated particle phenomena. *Ibid.*, 79, 3207–3210.

–»– , PIKKARAINEN, T., GOLIKOV, Yu., BARANSKY, L., TROITSKAYA, V.A. and V. STERLIKOVA, 1979: Bursts of irregular magnetic pulsations during the substorm. *J. Geophys.*, 46, 237–247.

–»– , BÖSINGER, T., and T. PIKKARAINEN, 1984: Short-period magnetic pulsations during the substorm. *Proc. Conf. Achievements of the IMS*, 26–28 June 1984, Graz, Austria, ESA SP-217, 599–602.

KAWAMURA, M., KUWASHIMA, M., TOYA, T., and H. FUKUNISHI, 1983: Comparative study of magnetic *Pc*1 pulsations observed at low and high latitudes: Long-term variation of occurrence frequency of the pulsations. *Mem. Natl Inst. Polar Res.*, Spec. Issue, 26, 1–12.

KENNEL, C.F., and H.E. PETSCHEK, 1966: Limit on stably trapped particle fluxes. *J. Geophys. Res.*, 71, 1–28.

KNAFLICH, H.B., and J.F. KENNEY, 1967: IPDP events and their generation in the magnetosphere. *Earth Planet. Sci. Lett.*, 2, 453–459.

KOZYRA, J.U., CRAVENS, T.E., NAGY, A.F., FONTHEIM, E.G., and R.S.B. ONG, 1984: Effects of energetic heavy ions on electromagnetic ion cyclotron wave generation in the plasmapause region. *J. Geophys. Res.*, 89, 2217–2233.

LEE, L.C., and Y.C. KWOK, 1984: A mechanism for the IPDP pulsations. *Ibid.*, 89, 877–882.

LIN, C.S., and G.K. PARKS, 1974: Further discussion of the cyclotron instability. *Ibid.*, 79, 2894–2897.

–»– , and G.K. PARKS, 1976: Ion cyclotron instability of drifting plasma clouds. *Ibid.*, 81, 3919–3922.

LOPEZ, J.A., 1982: Characteristics of irregular pulsations of diminishing periods (IPDP) at College, Alaska. *A Thesis Master of Science*, Fairbanks, *University of Alaska*, 1–79.

LUKKARI, L., KANGAS, J., and H. RANTA, 1977: Correlated electron precipitation and magnetic IPDP events near the plasmapause. *J. Geophys. Res.*, 82, 4750–4756.

MALTSEVA, N.F., GULYELMI, A.V., and V.N. VINOGRADOVA, 1970: Effect of the westward frequency drift in the intervals of pulsations with decreasing period. *Geomagn. Aeronomy,* 10, 745–747.

–»– , TROITSKAYA, V., GERAZIMOVITCH, E., BARANSKY, L., ASHEIM, S., HOLTET, J., AASEN, K., EGELAND, A., and J. KANGAS, 1981: On temporal and spatial development of IPDP source region. *J. Atmos. Terr. Phys.,* 43, 1175–1188.

–»– , KANGAS, J., PIKKARAINEN, T., and J. OLSON, 1986: Heavy ion populations in the magnetosphere and the generation of ULF ion cyclotron waves. To be published.

MATVEYEVA, E.T., TROITSKAYA, V.A., and A.V. GULELMI, 1972: The long-term statistical forecast of geomagnetic pulsations of type *Pc*1 activity. *Planet. Space Sci.,* 20, 637–638.

MAUK, B.H., 1982: Helium resonance and dispersion effects on geostationary Alfven/ion cyclotron waves. *J. Geophys. Res.,* 87, 9107–9119.

PERRAUT, S., 1982: Wave-particle interactions in the ULF range: GEOS-1 and -2 results. *Planet. Space Sci.,* 30, 1219–1227.

–»– , GENDRIN, R., ROUX, A., and C. de VILLEDARY, 1984: Ion cyclotron waves: Direct comparison between ground-based measurements and observations in the source region. *J. Geophys. Res.,* 89, 195–202.

PIKKARAINEN, T., KANGAS, J., KISELEV, B., MALTSEVA, N., RAKHMATULIN, R., and S. SOLOVJEV, 1983: Type IPDP magnetic pulsations and the development of their sources. *Ibid.,* 88, 6204–6212.

–»– , KANGAS, J., RANTA, H., RANTA, A., MALTSEVA, N., TROITSKAYA, V., and L. AFANASIEVA, 1986: Riometer absorption events in the evening-to-afternoon sector of the auroral and sub-auroral zone and movements of the IPDP source. *J. Atoms. Terr. Phys.* 48, 585–596.

RANTA, H., and A. RANTA, 1979: List of intervals for sharp onsets, afternoon side absorption events (»REP») and auroral absorption events in the recordings of the Finnish riometer chain during 1976–1978. *Geophysical Observatory, Sodankylä, Report No. 32,* 1–39.

RANTA, A., RANTA, H., ROSENBERG, T.J., WEDEKEN, U., and P. STAUNING, 1983: Development of an auroral absorption substorm: Studies of substorm related absorption events in the afternoon-early evening sector. *Planet. Space Sci.,* 31, 1415–1434.

RAUCH, J.L., and A. ROUX, 1982: Ray tracing of ULF waves in a multicomponent magnetospheric plasma: Consequences for the generation mechanism of ion cyclotron waves. *J. Geophys. Res.,* 87, 8191–8198.

ROUX, A., PERRAUT, S., RAUCH, J.L., DeVILLEDARY, C., KREMSER, G., KORTH, A., and D.T. YOUNG, 1982: Wave-particle interactions near Ω^{+}_{He} observed on board GEOS 1 and 2, 2. Generation of ion cyclotron waves and heating of He^{+} ions. *Ibid.,* 87, 8174–8190.

ROXBURGH, K.R., 1970: A theory for the generation of »Interval of pulsations of diminishing periods». *Ph.D. Thesis, University of British Columbia,* Vancouver, Canada.

SØRAAS, F., LUNDBLAD, J.Å., MALTSEVA, N.F., TROITSKAYA, V., and V. SELIVANOV, 1980: A comparison between simultaneous IPDP groundbased observations and observations of energetic protons obtained by satellites. *Planet. Space Sci.,* 28, 387–405.

THORNE, R.M., and C.F. KENNEL, 1971: Relativistic electron precipitation during magnetic storm main phase. *J. Geophys. Res.*, 76, 4446–4453.

–»– , 1974: A possible cause of dayside relativistic electron precipitation events. *J. Atmos. Terr. Phys.*, 36, 635–645.

–»– , and T.R. LARSEN, 1976: An investigation of relativistic electron precipitation events and their association with magnetospheric substorm activity. *J. Geophys. Res.*, 81, 5501–5506.

TROITSKAYA, V., and M. MELNIKOVA, 1959: About characteristic intervals of pulsations of diminishing periods. *DAN USSR*, **128**, 918 (in Russian).

–»– , 1961: Pulsation of the Earth's electromagnetic field with periods of 1 to 15 seconds and their connection with phenomena in the high atmosphere. *J. Geophys. Res.*, 66, 5–18.

–»– , SCHEPETNOV, R.V., and A.V. GULYELMI, 1968: Estimate of electric fields in the magnetosphere from the frequency drift of micropulsations. *Geomagn. Aeronomy*, 8, 634.

YOUNG, D.T., PERRAUT, S., ROUX, A., De VILLEDARY, C., GENDRIN, R., KORTH, A., KREMSER, G., and D. JONES, 1981: Wave-particle interactions near Ω^{+}_{He} observed on GEOS 1 and 2, 1. Propagation of ion cyclotron waves in He^{+}-rich plasma. *J. Geophys. Res.*, 86, 6755–6772.

–»– , BALSIGER, H., and J. GEISS, 1982: Correlations of magnetospheric ion composition with geomagnetic and solar activity. *Ibid.*, 87, 9077–9096.