COMPARATIVE STUDY OF MAGNETIC Pc1 PULSATIONS BETWEEN LOW LATITUDES AND HIGH LATITUDES: SOURCE REGION AND PROPAGATION MECHANISM OF THE WAVES DEDUCED FROM THE CHARACTERISTICS OF THE PULSATIONS AT MIDDLE AND LOW LATITUDES

Makoto KAWAMURA, Masayuki KUWASHIMA and Takeshi TOYA

Kakioka Magnetic Observatory, 595 Kakioka, Yasato-machi, Niihari-gun, Ibaraki 315-01

Abstract: The purposes of the present paper are to present some interesting morphological features of pc1 pulsations observed at low latitudes and to propose the most plausible model of generation and propagation of the pulsations. Comparison between the low-latitude pc1 and the high-latitude one will be done in our joint paper (KUWASHIMA *et al.*, 1981). In this paper, occurrence characteristics, the most important factors, of the pulsations are mainly investigated.

In the first place, some statistical features of the pulsations are shown on the basis of data obtained at Memambetsu, the northernmost one of the Japanese chain stations, during two-years period from June 1967 to May 1969. And the features of the diurnal and seasonal variations are compared with those of the electron density of the ionospheric F2 layer at Wakkanai which is located at a distance of about 200 km from Memambetsu. Next, conjugate relationships of the pulsations at middle and low latitudes are analyzed statistically on the basis of data obtained at Memambetsu, Japan and Newcastle and Hobart, Australia for the same two-years period. Relations between the occurrence and the development of the ring current (*Dst*) are also discussed. Moreover, the above conjugate relationships of the pc1 occurrence at middle and low latitudes are investigated in more detail in comparison of dynamic spectra obtained at Memambetsu and the Australian longitudinal chain stations, Mundaring, Woomera, Newcastle and Auckland, for the period of April 1–30, 1977.

These results suggest that the low-latitude pc1 has its source regien at the plasmapause latitudes and propagates to lower latitudes approximately along the connected geomagnetic meridians through the ionospheric wave duct. Finally, a plausible model of the generation and propagation is proposed.

1. Introduction

Continuous observations of the geomagnetic pulsations with period longer than about 10 s at our two branch observatories, Memambetsu and Kanoya, started in the IGY period, using old-type induction magnetometers which consist of air-cored sensors, galvanometers and rapid-run recorders (YOSHIMATSU, 1960). In the IQSY period, observation of pc1-range pulsations was added for each of the observatories. The observation was carried out with another type of induction magnetometer which consists of high-mu-metal-cored coils, dc amplifiers and a PWM data recorder (YASUI, 1967; KAWAMURA and KASHIWABARA, 1965). After that, these two observing systems were replaced with the present one (KAWAMURA, 1976, 1977). Moreover, similar observation at Chichijima has been established as one of the Japanese MONSEE plans. Since the IMS, continuous observation of the pulsations has been carried out at Kakioka. These four observatories will constitute a network of multiple surface stations in low latitudes.

Since the 1960's, the characteristics of pc1 pulsations have been analyzed with various types of dynamic spectral analyzers by many research workers (SAITO, 1960; HEACOCK and HESSLER, 1962; KATO and SAITO, 1964; TROITSKAYA, 1967; KAWAMURA, 1970; KOKUBUN, 1970; SAKURAI, 1975; FRASER, 1975; TOYA *et al.*, 1979). Meanwhile, the theoretical studies of the pc 1 characteristics have been also developed by many workers. The generation mechanism of the pulsations in the magnetosphere has been examined by CORNWALL (1965), JACOBS and WATANABE (1966) and GENDRIN (1970). TEPLEY and LANDSHOF (1966), MANCHESTER (1966) and GREIFINGER and GREIFINGER (1968, 1973) introduced the ionospheric duct propagation theory of the pc1 waves. In spite of the above-mentioned many research works, several important problems have remained pending in regard to the pc1 wave characteristics.

As for the exciting mechanism of the pc1 waves, the proton cyclotron instability model was proposed by CORNWALL (1965) and JACOBS and WATANABE (1966). In the cases where the beam velocity of trapped proton is supersonic with respect to the local Alfvén velocity, hydromagnetic waves with a frequency corresponding to the occurrence of the cyclotron resonance are emitted. It has been suggested that the particle energy of the storm-time ring current proton is transferred to the hydromagnetic wave energy through the instability. However, no significant relations between the generation of the pc1 waves and the geomagnetic activity (*Kp*, *Dst* and so on) have been reported until our previous paper (TOYA *et al.*, 1979).

The diurnal variation of the pc1 occurrence has not yet been clarified sufficiently. Actually, different types of the variation have been reported (BENIOFF, 1960; SCHLICH, 1963; KATO and SAITO, 1964; HEACOCK and HESSLER, 1965; TROITSKAYA, 1967; KOKUBUN and OGUTI, 1968; KAWAMURA, 1970). These results are summarized as follows: At high latitudes the occurrence maximum of the pc1 pulsations is in the daytime, whereas at low latitudes it is always in the nighttime. The time of the maximum occurrence seems to shift gradually from the daytime to the nighttime at about 60° in geomagnetic latitude. Such observational results will suggest that the pc1 pulsations consist of many kinds of sub-types. Therefore, it is very important in the study of the pc1 pulsations to clarify the relations between the high-latitude pc1 and the low-latitude one. Nevertheless, the relations have not yet been investigated systematically until our previous paper (TOYA *et al.*, 1979). Comparative studies of the pulsations between low and high latitudes are further developed in the present paper and our joint paper (KUWASHIMA *et al.*, 1981).

Another important theme is the ionospheric effect on the propagation of the waves from the source latitudes to lower and higher latitudes. According to the investigations by CAMPBELL and THORNBERRY (1972) and FRASER (1975), the pc1 waves show a remarkable westward propagation in the ionospheric duct, while the observation by ALTHOUSE and DAVIS (1978) shows that the propagation direction of the waves tends to coincide approximately with the geomagnetic meridian. Such an apparent contradiction in these observational results should be also clarified systematically. In the present paper, the characteristics of the wave propagation in the ionospheric duct are investigated on the basis of data at a middle- and low-latitude conjugate station-network which consists of the above-mentioned Japanese stations and an Australian station-chain.

On the basis of the observational facts derived from the present analysis, the generation mechanism of the pc1 observed at low latitudes and its propagation behaviors will be schematically illustrated in the summary section.

2. Diurnal and Seasonal Variations of Pc1 Occurrence at Memambetsu

Continuous observations of geomagnetic pulsations have been carried out at our Japanese stations, Memambetsu, Kakioka, Kanoya and Chichijima, with specially designed induction magnetometers and data recorders. In Fig. 1, diurnal variations of occurrence (upper frame) and mid-frequency (lower frame) of pc1 pulsations observed at Memambetsu, the northernmost station of the network, are shown (KAWAMURA and SANO, 1972). These results were obtained for two-years period, June 1967–May 1969, of the pre-IASY. Similar diurnal variation of the occurrence for two-years period, April 1964–March 1966, of the IQSY is also observed (KAWAMURA, 1970). In the upper frame of the figure, the diurnal variation averaged for these two periods are also superposed. In these investigations of the occurrence, we counted hourly numbers of 20-minutes interval in which any pc1 event was observed. As shown in the figure, pc1 occurrence at low latitudes concentrates in the night hours. It shows a distinct maximum at one or two hours before sunrise and then decreases rapidly and reaches a minimum around noon. It usually shows a comparatively low level throughout the daytime and increases again gradually after sunset. These results suggest that, in the night hours, pc1 waves can propagate more easily to lower latitudes without large attenuation, because the plasma density in the ionospheric duct will become lower in the hours. The mid-frequency of the pc1 also shows a remarkable diurnal variation which corresponds well to that of the occurrence.

To investigate such a tendency of the occurrence in more detail, pc1 occurrence at Memambetsu is compared with f_oF2 at Wakkanai. Wakkanai is located at a

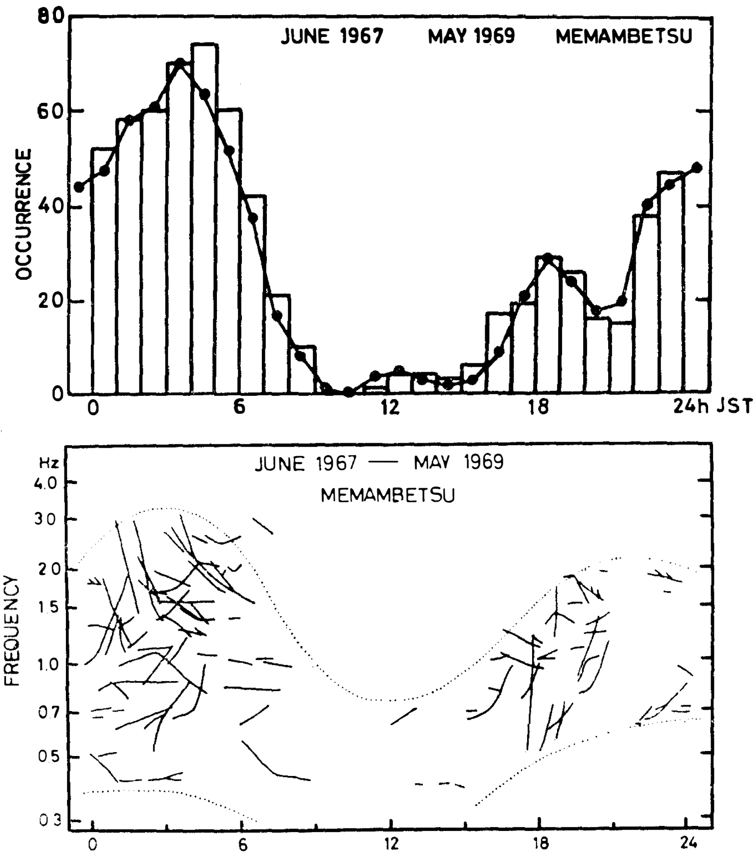


Fig. 1. Diurnal variations of occurrence (upper frame) and mid-frequency (lower frame) of pc1 pulsations observed at a low latitude station, Memambetsu (cf. KAWAMURA and SANO, 1972).

distance of about 200 km from Memambetsu. In Fig. 2, pc1 occurrence probability at Memambetsu (left frame) and f_oF2 at Wakkanai (right frame) are illustrated for the same two-years period from June 1967 to May 1969. The monthly hourly occurrence probability is calculated for each one-hour range of each month. In the figure, both pc1 occurrence probability and f_oF2 are divided into four steps, respectively. The blank space of the occurrence probability means that no pc1 event was observed in the corresponding monthly hourly ranges. The light dotted, the heavy dotted and the black areas indicate that the pulsations occurred with the probability ranging from 0 to 5%, from 5 to 10% and exceeding 10%, respectively. The blank space of the ionospheric f_oF2 corresponds to the monthly hourly ranges in which the averaged f_oF2 exceeds 10 MHz. The light dotted, the dark dotted and the black areas indicate that the f_oF2 is less than 10, 7 and 4 MHz, respectively. As shown in the figure, the smaller becomes the f_oF2 value, in other words, the lower becomes the ionospheric electron density, the higher is the pc1 occurrence probability. Namely, it is clearly

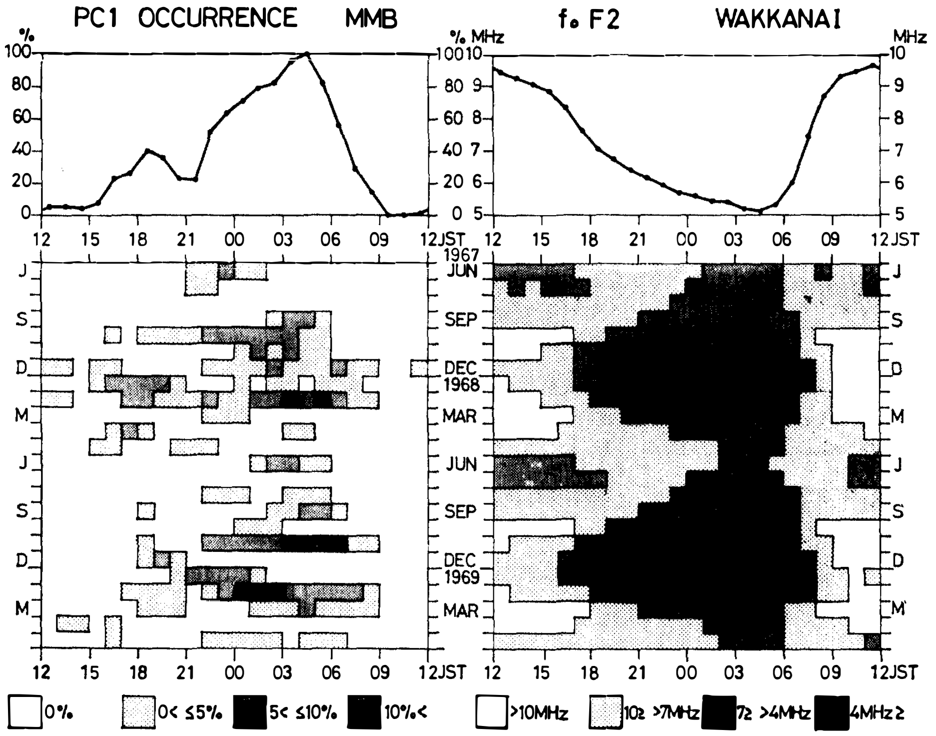


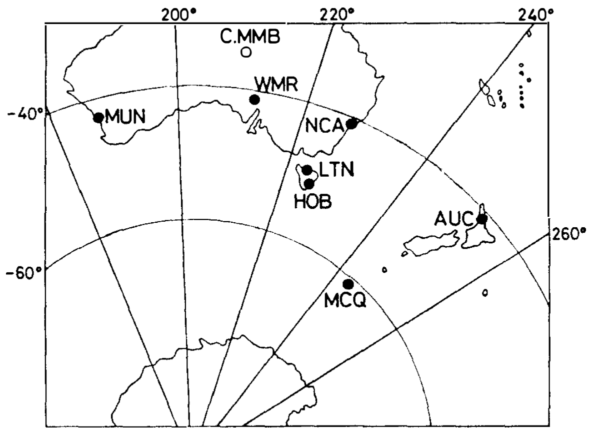
Fig. 2. Diurnal and seasonal variations of pc1 occurrence probability at Memambetsu (left frames) and f_oF2 at Wakkanai (right frames) for the same two-years period from June 1967 to May 1969.

seen that pc1 events at low latitudes are usually observed in night hours in which the plasma density in the ionospheric F2 layer becomes low. In the case of such a low f_oF2 condition, the ionospheric attenuation effect on the duct propagation of the pc1 waves may be reduced sufficiently and so the waves will be able to propagate easily in the duct from higher latitudes to lower ones. In the upper frame of the figure, diurnal variations of the pc1 occurrence and the f_oF2 which are averaged for the two-years period shown in the lower frame are summarized. The pc1 occurrence is normalized so that the maximum corresponds to 100%. The f_oF2 shows a clear minimum at about 04–05 h JST and the diurnal variation corresponds well to that of pc1 occurrence. After sunrise, the pc1 occurrence decreases rapidly with increase of the f_oF2. A clear maximum of the f_oF2 observed around noon corresponds to the minimum of the pc1 occurrence. After that, the pc1 occurrence increases again gradually with gradual decrease of the f_oF2. Similarly, it will be seen in the figure that the seasonal variation of the pc1 occurrence corresponds fairly well to that of the f_oF2. The f_oF2 shows a clear seasonal variation which has a distinct minimum in winter months. The pc1 events at low latitudes are observed most frequently in the winter months, but the seasonal variation is somewhat complicated in comparison with that of the f_oF2. For example, in December 1968, only a few events were observed at Memambetsu. As will be shown later, such facts may be related to the generation mechanism of the pcl waves in the magnetosphere. The characteristic diurnal and seasonal variations of the pcl occurrence at low latitudes suggest that the pcl waves which are generated in the magnetosphere under a favorable condition will be subjected to a considerable attenuation in the ionospheric propagation path.

3. Statistical Study of the Conjugate Relationship at Middle and Low Latitudes

Conjugate relationships of middle- and low-latitudes pcl are investigated statistically on the basis of data obtained at Memambetsu, Japan, and Newcastle and Hobart, Australia, during the two-years period from June 1967 to May 1969. The geomagnetic locations of the Australian chain stations and the conjugate point of Memambetsu are given in Fig. 3. Memambetsu and Woomera are located on the same geomagnetic meridian of about 210° and an approximate conjugate relationship exists between these two stations. Similarly, the geomagnetic longitudes of Newcastle and Hobert are very close. Namely, Newcastle-Hobert meridian is apart by about

GEOMAGNETIC LOCATION OF THE STATIONS



	STATION	GEOMAG. LAT.	GEOMAG. LONG.	L
C. MMB	CONJUGATE OF MEMAMBETSU	-34.3	209.7	1.5
MUN	MUNDARING	-43.3	187.9	1.9
WMR	WOOMERA	-41.3	211.4	1.8
NCA	NEWCASTLE	-40.8	228.0	1.8
AUC	AUCKLAND	-40.6	253.4	1.7
LTN	LAUNCESTON	-49.8	222.8	2.4
HOB	HOBART	-51.4	226.0	2.6
MCQ	MACQUARIE ISL.	-60.8	244.2	4.2

Fig. 3. Geomagnetic locations of the Australian chain stations and the conjugate point of Memambetsu (C. MMB).

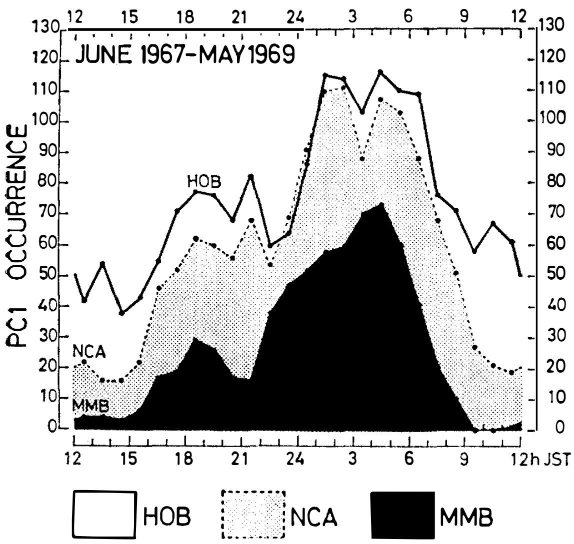


Fig. 4. Comparison of diurnal variations of pc1 occurrence among Memambetsu (L=1.5), Newcastle (L=1.8) and Hobart (L=2.6).

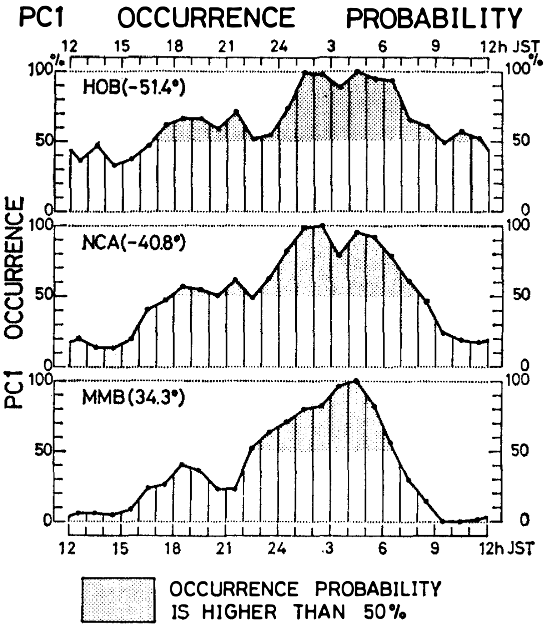


Fig. 5. Comparison of normalized diurnal variations of pc1 occurrence among Memambetsu, Newcastle and Hobart.

15° from Memambetsu-Woomera meridian and the difference of local time is at most one hour. Therefore, in this statistical study we neglected the difference of local time between Memambetsu and the Australian stations. In Fig. 4, diurnal variations of pc1 occurrence at Memambetsu, Newcastle and Hobart are compared with one another. In the figure, hourly occurrence numbers of 20-minutes interval in which any pc1 is seen are plotted. It is very clear in the figure that the characteristics of the diurnal variations observed at these stations are similar. The pc1 occurrence concentrates in night hours and shows the primary maximum around 04–05 h in local time. The secondary maximum around 18–17 h is also clearly seen at each station. However, the absolute occurrence number, N, of pc1 event is fairly different from each other. Namely, the number becomes larger with increasing geomagnetic latitude of the station:

$$N(HOB) > N(NCA) > N(MMB).$$

It should be noted that the above result is due to the difference of the attenuation effect on pc1 waves in the ionospheric duct. The lower is the geomagnetic latitude of the station, the longer becomes the propagation path of the pc1. In such a case, pc1 waves will be subjected to the ionospheric attenuation more intensely.

Not only the absolute numbers but also the diurnal variations of the pc 1 occurrence at these three stations are fairly different from each other, as shown in Fig.

5. Pcl occurrence at each station is so normalized that the maximum occurrence corresponds to 100%. It will be seen in the figure that the diurnal variation becomes clear with decreasing geomagnetic latitude of station. In the figure, the dotted area means the hours in which such a normalized hourly occurrence of the pcl at each station exceeds 50%. At Memambetsu, the area is usually restricted to about 10 hours from pre-midnight to sunrise. However, the area expands to the dayside with increasing geomagnetic latitude. This fact also indicates that the lower is the geomagnetic latitude of station, the more intense becomes the ionospheric attenuation of the pcl amplitudes. Moreover, the above result will suggest that Hobart is located near the pcl source region.

4. Relation between Development of Ring Current (*Dst*) and Pcl Occurrence

In Fig. 6, monthly occurrences of the pcl at Memambetsu and Newcastle are shown together with the difference between these two stations. It will be noticed at first sight that the occurrence peaks at the stations correspond fairly well with each other. In the right frame of the figure, *Hc* (monthly mean geomagnetic horizontal

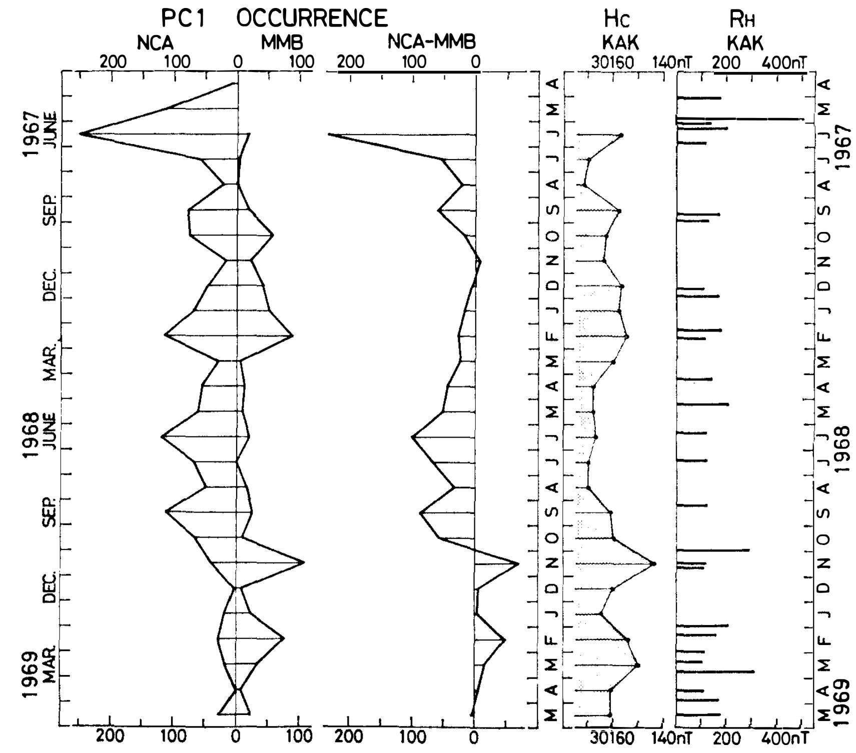


Fig. 6. (Left frame): Monthly occurrences of pcl pulsations at Memambetsu and Newcastle as well as difference of the occurrences between these two stations. (Right frame): Monthly mean value (Hc) and maximum storm range (R_H) of geomagnetic horizontal component at Kakioka.

component corrected for its non-cyclic secular variation) and R_H (maximum storm range of H) observed at Kakioka are given. The *Hc* was used instead of usual equatorial *Dst* index as a measure of development of the ring current. In the figure it will be clearly seen that the pc1 occurrence peaks also correspond to the development of the *Dst* and the occurrences of intense geomagnetic storms.

Seasonal variation of the pc1 occurrence is also seen in the figure. As already described, the pc1 event will be observed more frequently in winter months: November–February at Memambetsu in the northern hemisphere and May–August at Newcastle in the southern hemisphere. On the contrary, the pc1 occurrence will be low in summer months. Such a relation is also seen clearly in the figure of the difference of the pc1 occurrence. Namely, the difference, N(NCA)–N(MMB), shows maxima and minima in winter and summer months in the southern hemisphere, respectively. The seasonal variation is also more distinct at the lower latitude station, Memambetsu, than at Newcastle. Such a tendency is consistent with the previous result that the diurnal variation is more clearly seen at lower latitude stations.

As shown above, parallel variations of the pc1 occurrence at Memambetsu and at Newcastle are also seen in connection with the development of the ring current. For example, pc1 occurrence at Newcastle was very high in June 1967, while that at Memambetsu was also relatively high in spite of the summer solstice in the northern hemisphere. As shown in the figure, large magnetic storms occurred successively during the period from May to June, 1967, following the clear increase of the pc1 occurrence. During the period from July to August, 1967, any remarkable magnetic storm did not occur, and at Memambetsu and Newcastle only a few pc1 events were

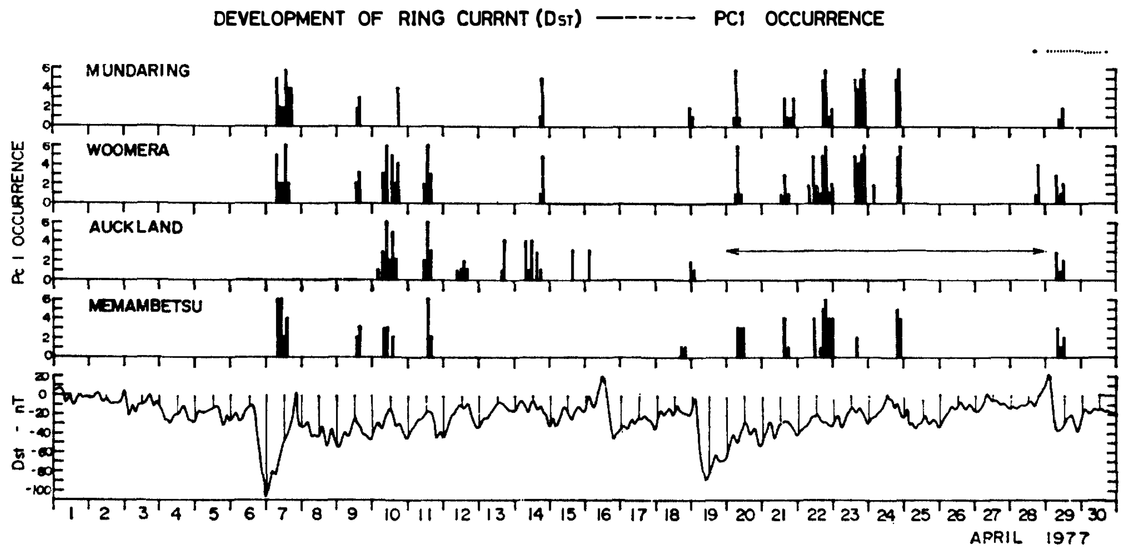


Fig. 7. Development of equatorial ring current (Dst) and pc1 occurrences at Memanbetsu and the Australian longitudinal chain stations.

observed. Successive magnetic storms again occurred in September 1967, and the pc1 events at these two stations were also active. In spite of the winter season in the northern hemisphere, the pc1 occurrence at Memambetsu was infrequent in November 1967, corresponding to the lack of intense magnetic storm in this month. In other words, pc1 occurrence is closely related to a large magnetic storm, namely, to a development of the ring current. Therefore, the pc1 occurrence at middle and low latitudes should be investigated in relation to both the attenuation effect in the ionospheric duct and the development of the ring current (*Dst*).

In Fig. 7, the relation between the development of the *Dst* and the pc1 occurrence is illustrated. In the figure, the pc1 occurrences at Memambetsu and at an Australian longitudinal chain which consists of four stations, Mundaring, Woomera, Newcastle and Auckland, are shown in detail for the period of April 1977. The *Dst* index is also given at the bottom of the figure. A distinct development of the *Dst* is seen on the 6th. The *Dst* recovered rapidly on the 7th. In the recovery phase, the pc 1 activity increased at both Memambetsu and the Australian stations. For several days from the 8th, small developments and decays of the *Dst* occurred successively and the pc1 events were also observed very frequently. Similar relation is also seen for the interval from the 19th to the 24th. It should be noted that the pc1 events at lower latitudes appear frequently in the recovery phase of a large magnetic storm.

As shown in the figure, pc1 seen at Memambetsu is also observed at Woomera which is located approximately on the same geomagnetic meridian as Memambetsu. However, pc1 is not always simultaneously observed at Memambetsu and at the other stations, Mundaring and Auckland. Successive pc1 events seen at Mundaring, Woomera and Memambetsu on the 7th were not at all observed at Auckland, whereas the events on the 11th were observed at the other three stations except Mundaring. These results suggest that the pc1 propagates approximately along the geomagnetic meridian. Geomagnetic locations of the stations used in the analysis are also shown in Fig. 3.

5. Latitudinal and Longitudinal Profiles of the Pc1 Amplitude

First, two examples of dynamic spectrum observed simultaneously at our Japanese station network are illustrated in Fig. 8, together with a map which shows the geomagnetic locations of the stations. Memambetsu, Kakioka and Chichijima are located almost on the same meridian of about 210°, but Kanoya is apart by about 10° westwards from this meridian. It will be noted that the pc1 event on January 18, 1976 was distinct on the Memambetsu-Chichijima meridian but at Kanoya only a weak trace was observed, while the pc1 event on March 16, 1976 was the most intense at Kanoya. As shown in the figure, pc1 amplitude is always larger at higher latitude station, Memambetsu, than at lower latitude one, Chichijima, on the same

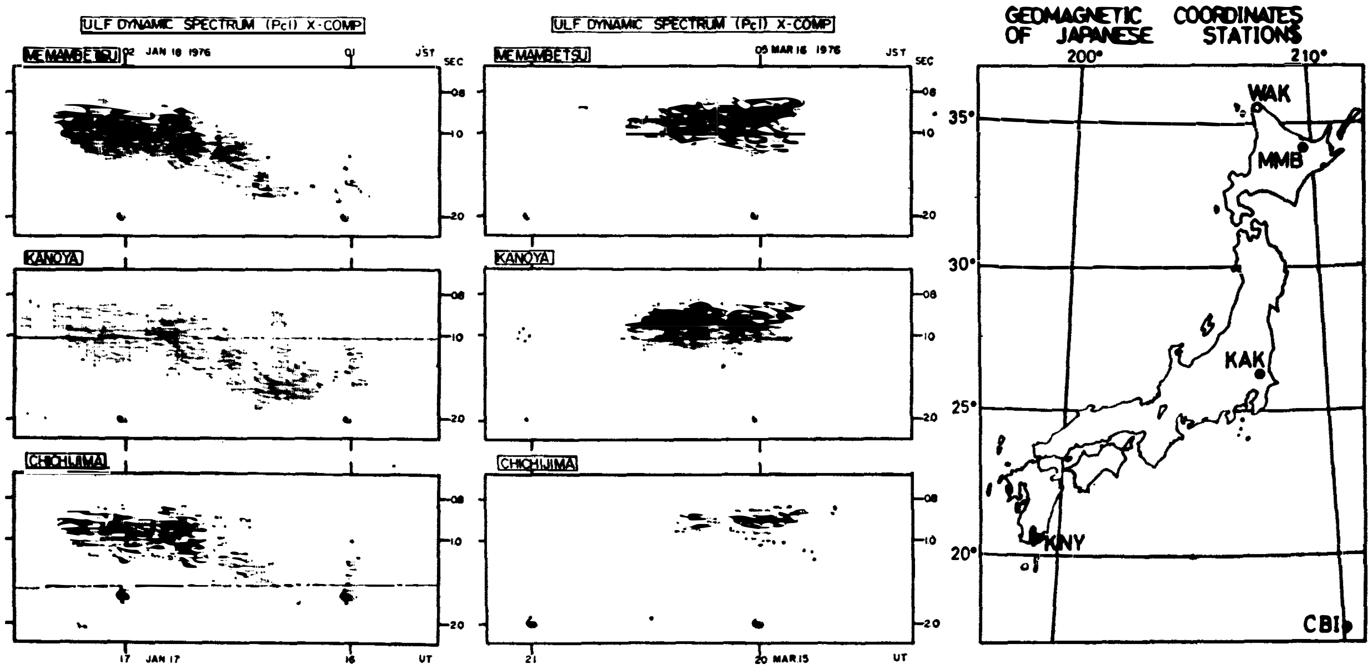


Fig. 8. Two examples of pc1 dynamic spectrum observed at the Japanese stations and geomagnetic locations of the stations.

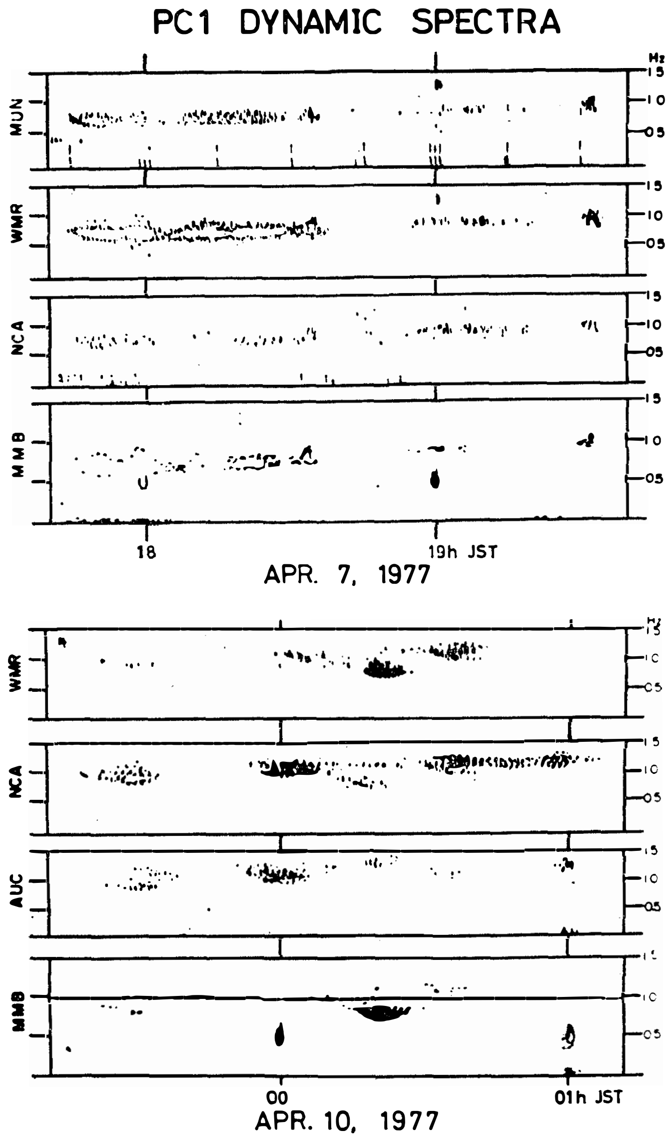


Fig. 9. Comparison of pc1 dynamic spectrum between Memambetsu and the Australian longitudinal chain stations.

geomagnetic meridian, and a longitudinal effect is also clearly seen between these two meridians. Namely, pc1 amplitude at Kanoya is sometimes larger than that at Memambetsu and sometimes smaller than that at Chichijima.

These facts suggest that the pc1 waves observed at low latitudes will propagate along the geomagnetic meridians from higher to lower latitudes and also may be subjected to intense attenuations on the propagation path. This is already discussed in more detail in our previous paper (TOYA *et al.*, 1979).

In the next place, conjugate relationships of the pc1 occurrence at middle and low latitudes will be investigated on the basis of data obtained at Memambetsu and at the aforesaid Australian longitudinal chain stations, Mundaring, Woomera, Newcastle and Auckland. As shown in Fig. 3, the geomagnetic longitudes of these Australian stations range from about 190° to about 250°, while the Australian stations are located at almost the same geomagnetic latitude of about 41°S and the latitude is higher by about 7° than that of Memambetsu. Two typical examples of the pc1 dynamic spectrum observed simultaneously at Memambetsu and the Australian stations are illustrated in Fig. 9. As shown in the figure, microstructures of the spectra observed at these stations are quite similar to each other, while the amplitudes of the pulsations are fairly different between the stations. As already described, an approximate conjugate relationship exists between Memambetsu and Woomera and then the pc1 pulsations are usually simultaneously observed at the stations. Anyhow, it is a very important result that the spectral structures are quite similar at Memambetsu and at the Australian stations which range over 65° in longitude but the spectral intensities are greatly different from each other. This fact means that pc1 waves with a common source, which will bounce between conjugate ionospheres along the field lines and propagate from higher latitudes to lower ones, are usually observed at these stations and the amplitudes of the waves are subjected to severe attenuation on the ionospheric propagation path.

As shown in the upper frame of the figure, in the event at about 18 h JST on April 7, 1977, the pc1 amplitude was the largest on the Woomera-Memambetsu meridian. The amplitudes at Newcastle and at Mundaring were less than those at Memambetsu and at Woomera, whereas at Auckland any pc1 activity was not seen. It will be deduced from the above facts that the waves propagated through the ionospheric duct which was located near the meridian of Woomera and Memambetsu. Moreover, the amplitude at Memambetsu was less than that at Woomera on the same meridian and the fact will suggest the already-described ionospheric attenuation effect on the waves. On April 9–10, 1977 (in the lower frame of the figure), successive pc1 events were observed at the stations. An event at about 2330 on the 9th showed the largest amplitude at Newcastle and the weak trace was seen at Auckland. However, on the Woomera-Memambetsu meridian the event was not observed. Another event at about 0 h JST on the 10th was clearly seen at Newcastle and at Auckland. The weak trace was also observed at Woomera but was not at all seen at Memambetsu and at Mundaring. It seems that the sources of these events were located near the meridian of Newcastle. On the contrary, the pc1 event seen at about 0020 was remarkable at the Woomera-Memambetsu meridian but was not at all observed at the other stations. It will be deduced that the pc1 seen at about 0030 JST had its source region on the meridians between Newcastle and Woomera, because it was observed only at these two stations. At Newcastle, the event seems to have continued for about 40 minutes, while at Woomera the duration of the event was at most 15 minutes and disappeared completely at 1 h JST. These results will suggest that such pc1 pulsa-

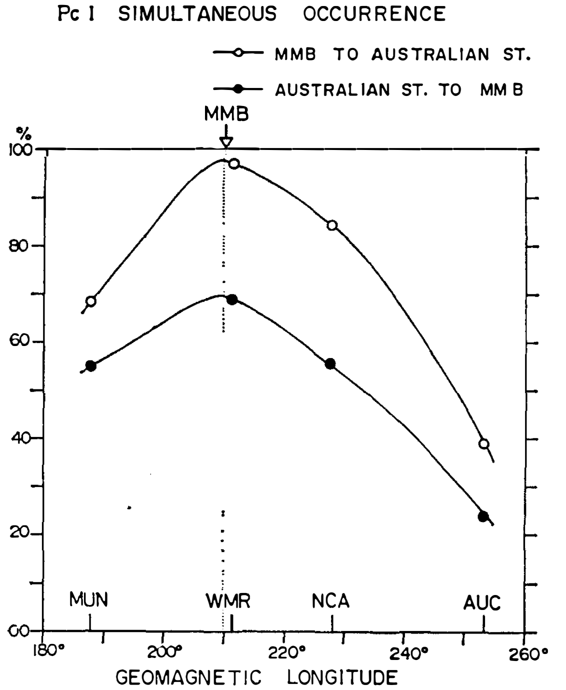


Fig. 10. Probability of simultaneous occurrence of pc1 between Memambetsu and the Australian longitudinal chain stations.

tions are usually the succession of events from different source regions and the duration of the individual event is at most 10–20 minutes and also such an individual event which ranges 20–30° in longitude from the source meridian is very infrequent.

The above longitudinal and latitudinal effects are summarized quantitatively in Fig. 10, in which the probabilities of simultaneous occurrence of the pc1 between Memambetsu and the Australian stations are shown. In the figure, the upper curve shows the probability at the Australian stations when a pc1 event was observed at Memambetsu. The curve indicates that almost all pc1 events observed at Memambetsu are also seen at Woomera. The probability was about 98%. The simultaneous occurrence probability decreases with increasing distance from the Memambetsu-Woomera meridian. At Auckland, the probability is less than 40%. The lower curve shows the probability at Memambetsu when a pc1 event was observed at the corresponding Australian station. The simultaneity of the pc1 occurrence is also the highest between Woomera and Memambetsu and the probability decreases with increasing distance from the Woomera-Memambetsu meridian. The probability at Auckland was only 20%. The difference between the upper and lower curves is mainly due to the difference of the geomagnetic latitude, that is, the difference of the ionospheric attenuation effect on the pc1 waves between Memambetsu and the Australian stations. Namely, the longer the propagation path is, the more intensely the waves will be subjected to the attenuation. Such latitudinal and longitudinal profiles of the pc1 amplitudes will be interpreted as a decisive evidence which shows the duct propagation of the waves along the geomagnetic meridians at middle and low latitudes.

6. Summary of the Recent Study and the Future Problems

In the present study, we were able to show some interesting morphological features of the pc1 pulsations observed at low latitudes. These features will be summarized as follows:

(1) Pc1 pulsations are observed usually in the recovery phase of a large magnetic storm. This fact means that the occurrence of pc1 pulsations at low latitudes should be closely related to the development of a ring current.

(2) Pc 1 pulsations at low latitudes show characteristic diurnal and seasonal variations of the occurrence frequency. These variations correspond well to those of the ionospheric f_oF2, namely, the occurrence probability of the pulsations at low latitudes increases with decreasing electron density of the F2 layer. Therefore, the variations of the occurrence (or the amplitude) can be explained by the attenuation effect which acts on the pulsations (waves) in the ionospheric duct in the first order approximation.

(3) The pc1 observed simultaneously at both Memambetsu and the Australian stations shows usually a very similar spectral structure. This fact means that the pc1 event observed at the Japanese stations has a common source with that observed at the Australian stations. Namely, the pc1 shows a clear conjugate relationship also at middle and low latitudes.

(4) The probability of simultaneous occurrence of the pc1 at Memambetsu and at the Australian stations has some distinct latitudinal and longitudinal profiles. Namely, the probability decreases with increase of longitudinal distance from the source meridian and with increase of latitudinal distance at the source meridian. These facts also suggest that pc1 waves propagate along the geomagnetic meridian and are subjected to a large attenuation in the ionospheric propagation path.

The above conclusions are also summarized and illustrated in Fig. 11. As shown in the figure, the pc1 observed at low latitudes occurs near the plasmapause in the recovery phase of an intense geomagnetic storm by wave-particle interaction. The pc1 waves bounce between the conjugate ionospheres along the field lines near the plasmapause and propagate from the plasmapause latitude to lower latitudes through the wave-duct in the ionospheric F2 layer in which the Alfven wave velocity has a minimum value. The wave propagates nearly along the geomagnetic meridian which connects the conjugate ionospheres, and the source region of the individual event is usually not so large. The wave is subjected to an attenuation in the ionospheric propagation path, and so the diurnal and seasonal variations of the occurrence frequency of the pc1 are related closely to those of the electron concentration of the ionospheric F2 layer. Therefore, not only the latitudinal profile of the pc1 intensity

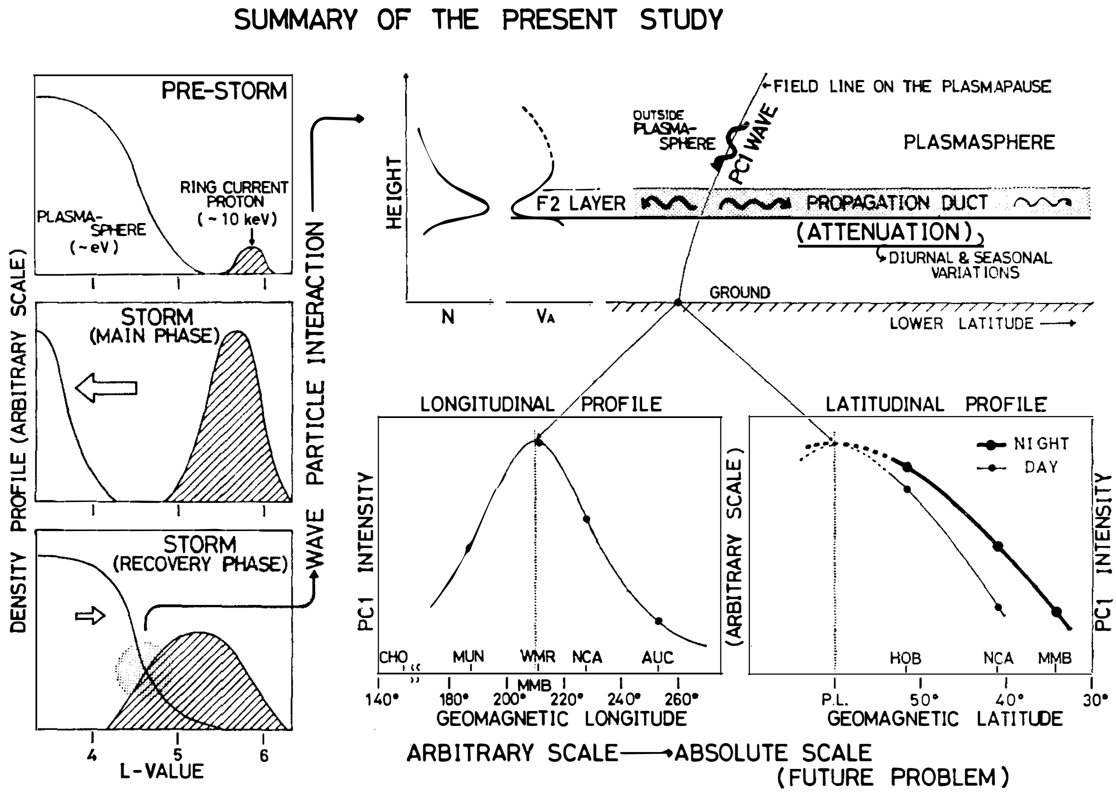


Fig. 11. An illustrative model for generation and propagation mechanisms of low latitude pc1 pulsations.

but also the variations of the pc1 occurrence will be interpreted by the ionospheric attenuation effect. Moreover, the longitudinal profile of the pc1 intensity reflects the dimensions of the magnetospheric source region and suggests the meridional propagation of the wave.

In the present paper, some features relative to the occurrence frequency of the pc1 have been analyzed mainly. However, the features of the period such as dispersion, cutoff-frequency and repeating periodicity, are also very important. Therefore, such features will be investigated in the near future. Moreover, a detailed quantitative comparison of the pc1 events between Japanese and Australian stations as well as an approach from theoretical aspects are also our future problems.

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References

ALTHOUSE, E. W. and DAVIS, J. R. (1978): Five-station observations of Pc 1 micropulsation propagation. J. Geophys. Res., **83**, 132–144.

BENIOFF, H. (1960): Observations of geomagnetic fluctuations in the period range 0.3 to 120 seconds. J. Geophys. Res., **65**, 1413–1422.

CAMPBELL, W. H. and THORNBERRY, T. C. (1972): Propagation of Pc 1 hydromagnetic waves across North America. J. Geophys. Res., **77**, 1941–1950.

CORNWALL, J. M. (1965): Cyclotron instabilities and electromagnetic emission in the ultra low frequency and very low frequency ranges. J. Geophys. Res., **70**, 61–69.

FRASER, B. J. (1975): Ionospheric duct propagation and Pc 1 pulsation sources. J. Geophys. Res., **80**, 2790–2796.

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

GREIFINGER, C. and GREIFINGER, P. (1968): Theory of hydromagnetic propagation in the ionospheric wave guide. J. Geophys. Res., **73**, 7473–7490.

GREIFINGER, C. and GREIFINGER, P. (1973): Wave guide propagation of micropulsations out of the plane of the geomagnetic meridian. J. Geophys. Res., **78**, 4611–4629.

HEACOCK, R. R. and HESSLER, V. P. (1962): Pearl-type telluric current micropulsations at College. J. Geophys. Res., **67**, 3985–3996.

HEACOCK, R. R. and HESSLER, V. P. (1965): Pearl-type micropulsations associated with magnetic storm sudden commencements. J. Geophys. Res., **70**, 1103–1111.

JACOBS, J. A. and WATANABE, T. (1966): Amplification of hydromagnetic waves in the magnetosphere by a cyclotron instability process with applications to the theory of hydromagnetic whistlers. J. Atmos. Sci., **28**, 235–253.

KATO, Y. and SAITO, T. (1966): Observation of pc1 and pi1 by a visual type induction magnetometer at middle latitude station, Onagawa. Rep. Ionos. Space Res. Jpn, **18**, 188–196.

KAWAMURA, M. (1970): Short-period geomagnetic micropulsations with period of about 1 second in the middle and low latitudes. Geophys. Mag., **17**, 7–18.

KAWAMURA, M. (1976): Report of the Geomagnetic and Geoelectric Observations, 1975, (Rapid Variations). Kakioka, Kakioka Magn. Obs., IV, 67 p.

KAWAMURA, M. (1977): Report of the Geomagnetic and Geoelectric Observations, 1976, (Rapid Variations). Kakioka, Kakioka Magn. Obs., IV, 55 p.

KAWAMURA, M. and KASHIWABARA, S. (1965): Observations of geomagnetic and earth-current micropulsations with period of about 1 cps. I. On the observing apparatus of geomagnetic micropulsations. Mem. Kakioka Magn. Obs., **12**, 1–13.

KAWAMURA, M. and SANO, Y. (1972): Some characteristics of pc1 micropulsations. Mem. Kakioka Magn. Obs., **14**, 9–18.

KOKUBUN, S. and OGUTI, T. (1968): Hydromagnetic emissions associated with storm sudden commencements. Rep. Ionos. Space Res. Jpn, **22**, 45–59.

KOKUBUIN, S. (1970): Fine structure of ULF emissions in the frequency range of 0.1–2 Hz. Rep. Ionos. Space Res. Jpn, **24**, 24–44.

KUWASHIMA, M., TOYA, T., KAWAMURA, M., HIRASAWA, T., FUKUNISHI, H. and AYUKAWA, M. (1981): Comparative study of magnetic Pc1 pulsations between low latitudes and high latitudes: Statistical study. Mem. Natl Inst. Polar Res., Spec. Issue, **18**, 101–117.

MANCHESTER, R. N. (1966): Propagation of pc1 micropulsations from high to low latitudes. J. Geophys. Res., **71**, 3749–3754.

SATO, T. (1960): Period analysis of geomagnetic pulsations by a sona-graph method. Sci. Rep. Tohoku Univ., Ser. 5 (Geophys.), **12**, 105–113.

SAKURAI, T. (1975): Variations of magnetospheric convection electric fields during substorms as inferred from pc1 hydromagnetic waves. Planet. Space Sci., **23**, 611–618.

SCHLICH, R. (1963): Micropulsations de periodes comprise entre 0.5 et 6 s observees dans les regions de hautes et moyennes latitudes. Ann. Geophys., **19**, 347–355.

TEPLEY, L. R. and LANDSHOFF, R. K. (1966): Waveguide theory for ionospheric propagation of hydromagnetic emissions. J. Geophys. Res., **71**, 1499–1504.

TOYA, T., KUWASHIMA, M. and KAWAMURA, M. (1979): Comparative study of magnetic pc-type pulsations between the low-latitudes and the high-latitudes (I): Statistical features of pc1 pulsations. Mem. Kakioka Magn. Obs., **18**, 29–47.

TROITSKAYA, V. A. (1967): Micropulsations and the state of the magnetosphere. Solar-Terrestrial Physics, ed. by J. W. KING and W. S. NEWMAN. New York, Academic Press, 213–274.

YASUI, Y. (1967): Report of Observations on Geomagnetism, Earth-Current and Night Airglow during the International Years of the Quiet Sun, 1964–1965. Kakioka, Kakioka Magn. Obs., IV, 227 p.

YOSHIMATSU, T. (1960): Report of the Geomagnetic and Geoelectric Observations during the International Geophysical Year, 1957–1958. Kakioka, Kakioka Magn. Obs., VIII, 487 p.

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