Comparative Study of Magnetic Pc-Type Pulsations at Low and High Latitudes (II) —Pc 3 Pulsations

Makoto KAWAMURA*, Yukizo SANO* and Masayuki KUWASHIMA**

低緯度および高緯度における Pc 型地磁気脈動の特性の対比 (II) —Pc 3 型脈動

河村　譜*・佐野幸三*・桑島正幸**

要旨: われわれの地磁気脈動観測所網のなかで最も北にある女満別の資料を用い，低緯度 Pc 3 の周期・出現頻度の諸変化の特性を統計的に調べた．次に Pc 3 の波形・スペクトル特性により，低緯度 (Hermanus) から極光帯 (昭和基地) にわたるその特性を比較した．えられた結果は次のように要約される．

1) 周期の太陽周期変化・日変化は，プラズマ圏のサイズ変化・非対称性によって説明される．また June solstice に最も短かくなる特徴のある周期の年変化がある．

2) 出現頻度は，地磁気活動度に依存する太陽周期変化・年変化をする．最大頻度・最短周期の出現時刻は，地磁気活動度の増加につれて正午直前から朝側に移行する．

3) 低緯度では周期・出現時間に大きな日々変化があるが，高緯度では日による変化は小さい．その出現は広い緯度範囲でよく対応するが，スペクトル成分は緯度依存性をもち，特に低緯度 Pc 3 は複雑な成分を含む．

Abstract: Four observatories, Memambetsu, Kakioka, Kanoya and Chichijima, constitute Japanese meridian-chain stations for the study of geomagnetic pulsations.

Using mainly the data obtained at Memambetsu which is the northernmost one of these observatories, characteristics of the long-term and diurnal variations of mean period and occurrence frequency of Pc 3 observed at low latitudes were investigated statistically. Then, the characteristics were compared with those at higher latitudes (auroral zone and plasmapause). In the analysis, autopower spectrum and dynamic spectrum of Pc 3-range pulsations observed at the Syowa meridian-chain stations, Syowa Station, SANAE and Hermanus, were used mainly.

The results are summarized as follows:

1) There is a solar-cycle variation in the mean period of Pc 3. The varia-

* 気象庁地磁気観測所. Magnetic Observatory, 595, Kakioka, Yasato-machi, Niihari-gun, Ibaraki 315–01.

** 気象庁地磁気観測所女満別出張所. Magnetic Observatory, 62 Showa, Memambetsu-cho, Abashiri-gun, Hokkaido 099–23.

tion can be related closely to the change in size of the plasmasphere

2) Pc 3 period shows such a characteristic annual variation as to become the shortest at the summer solstice.

3) Solar-cycle and seasonal variations of occurrence frequency of Pc 3 represent clearly dependence of the frequency on the geomagnetic activity.

4) Pc 3 is a daytime phenomenon which has an occurrence peak just before noon, but the peak shifts to earlier hours of day as the geomagnetic activity heightens.

5) Diurnal variation of the period of Pc 3 shows "Inverted-U type" only in the summer of sunspot maximum years (1957–1961). In the other seasons and in the sunspot minimum years it is not so clear or shows rather "U type". However, on highly disturbed days the period shows a characteristic diurnal variation and the time when it becomes the shortest shifts to the morning side.

6) Pc 3 has a good correlation in its activity over a wide latitudinal range, but the spectral components at low latitudes are very different from those at higher latitudes.

1. Introduction

Since the IGY, geomagnetic pulsations with period longer than about 10 sec have been observed continuously at our two observatories, Memambetsu and Kanoya. Early instruments at these observatories were classical-type induction magnetographs which consisted of air-cored loops, galvanometers and rapid-run photographic recorders (YOSHIMATSU, 1960). Occurrence time, amplitude and period of pulsation were hand-scaled on the record Driving speed of the recorder was 12 mm/s. Afterwards, each instrument has been replaced with the present one which consists of three orthogonal parmalloy-cored coils, dc amplifiers and an FM data recorder (KAWAMURA, 1976, 1977) Since 1974, the same type magnetometers have also been installed at Chichijima. In the IMS period, similar observation has been started at Kakioka with a compact instrument. All of these instruments have almost the same overall response character. The pulsations recorded on the magnetic tape by the data recorder at each observatory are reproduced and analyzed at Kakioka. Details of these recording and analyzing systems are given in the previous papers (KAWAMURA and KUWASHIMA, 1977; KUWASHIMA *et al.*, 1979). Moreover, some trouble spectral analyses were carried out with the specially designed spectral analysis system of the National Institute of Polar Research (IWABUCHI *et al.*, 1978).

Geomagnetic coordinates of these four observatories are shown in Fig. 1. It should be noted that the observatories are located along almost the same meridian of about 208° in longitude. The latitudes range from 34.0° to 17.1°. We put a stress on the Memambetsu data in the present paper because Pc 3 characteristics were almost

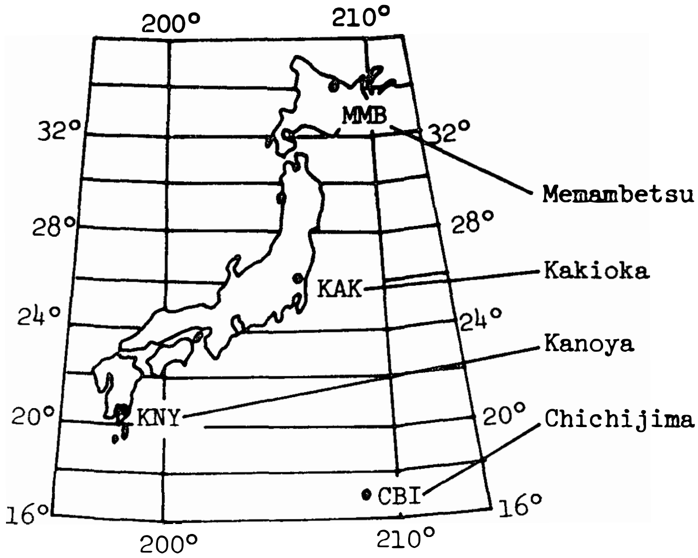

Fig. 1. Geomagnetic coordinates of the four observatories forming a Japanese station-chain.

the same at these observatories. And the data of SANAE and Hermanus were presented by Dr. BARKER and the Hermanus Observatory, respectively.

2. Solar Cycle Variation of Pc 3 Period

The solar cycle variation of yearly average period of Pc 3 at Memambetsu for eleven years from 1957 to 1967 is illustrated in Fig. 2 together with yearly average

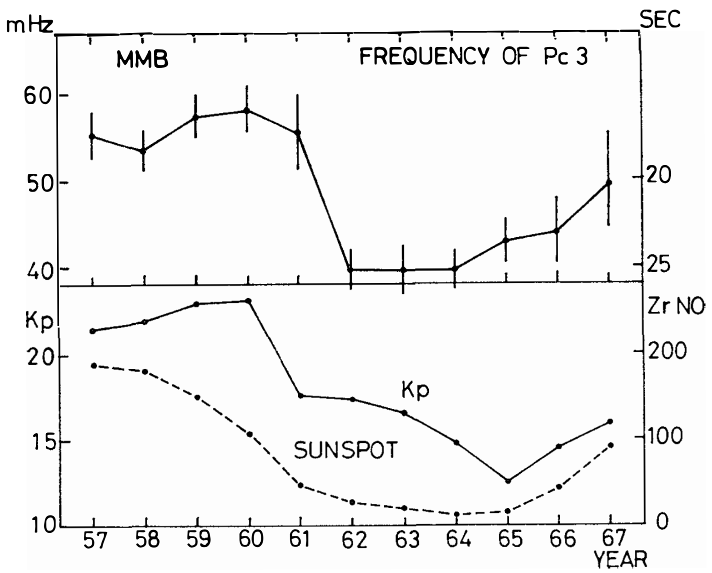

Fig. 2. Solar cycle variations of period of Pc 3 at Memambetsu, ΣKp and the relative sunspot number for eleven years from 1957 to 1967.

values of $\sum Kp$ and relative sunspot number. The average period is calculated from the mean period of the pulsation hand-scaled for each special interval with quality of A or B (ROMAÑÁ, 1960) reported in successive issues of our annual report "Report of the Geomagnetic and Geoelectric Observations (Rapid Variations)". As shown in this figure, the average period corresponds well to the $\sum Kp$ and/or the sunspot number. But there is usually a time lag between solar and geomagnetic activities. Although the sunspot maximum year during these years was the year 1957, the shortest average period was observed in 1960 coinciding with the peak of $\sum Kp$ rather than with the sunspot maximum. The variation in yearly average period of Pc 3 observed at Onagawa for the following ten years was investigated by SAITO *et al.* (1977) and the results are shown in the upper frame of Fig. 3. It is clear in these figures that the period in the sunspot

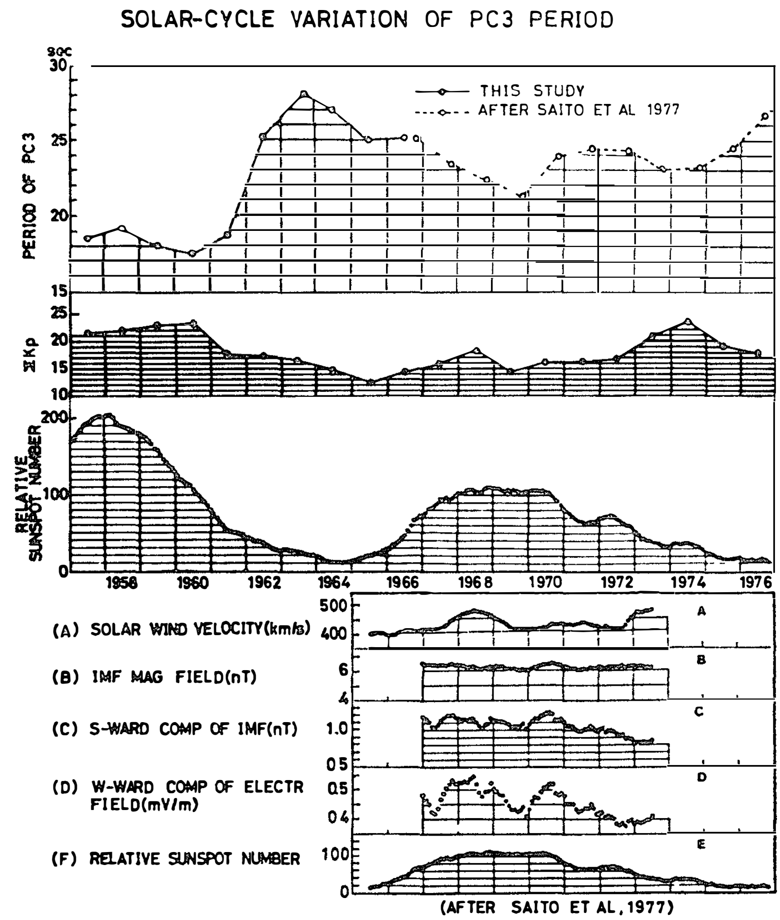

Fig 3. (Upper) Solar cycle variations of period of Pc 3 at Onagawa, ΣKp and the relative sunspot number for eleven years from 1966 to 1976 (after SAITO et al, 1977). (Lower): Solar cycle variations of solar wind velocity (A), magnitude of IMF (B), southward component of IMF (C), westward component of electric field (D) and the relative sunspot number (E) (after SAITO et al, 1977)

maximum phase is distinctly shorter than that in the minimum phase. Moreover, the period is likely to be related more closely to the geomagnetic activity. For example, a minimum of the period in the year 1974 when the relative sunspot number has a fairly low value of 34.5 corresponds clearly to the unusual high geomagnetic activity in the year. The period which was about 18 sec in the geomagnetically disturbed years (1957–1960) became longer as the activity decreased and reached 25 sec or more in the quiet years (1962–1965). The approximately negative correlation between the average period of Pc 3 and the geomagnetic activity (or the relative sunspot number) still continued to the subsequent years.

As shown in the lower frame of Fig. 3, the solar cycle variation for years from 1966 to 1976 was investigated by SAITO *et al.* (1977) in more detail. They compared the variation with those of interplanetary factors. Those are solar wind velocity (A), magnitude of interplanetary magnetic field (B), southward component of interplanetary magnetic field (C), westward component of convection electric field (D) and relative sunspot number (E). The convection electric field also shows a solar cycle variation, so that the solar cycle variation of the period of Pc 3 may be interpreted as the result of the solar cycle variation of the electric field. The magnitude of the convection electric field will be closely related to the size of the plasmasphere. This fact means that we can monitor the size of the plasmasphere by means of such a ground-based continuous observation of the low-latitude Pc 3.

3. Annual Variation of Pc 3 Period

In Fig. 4 the annual variation of an averaged period of Pc 3 is shown. The left

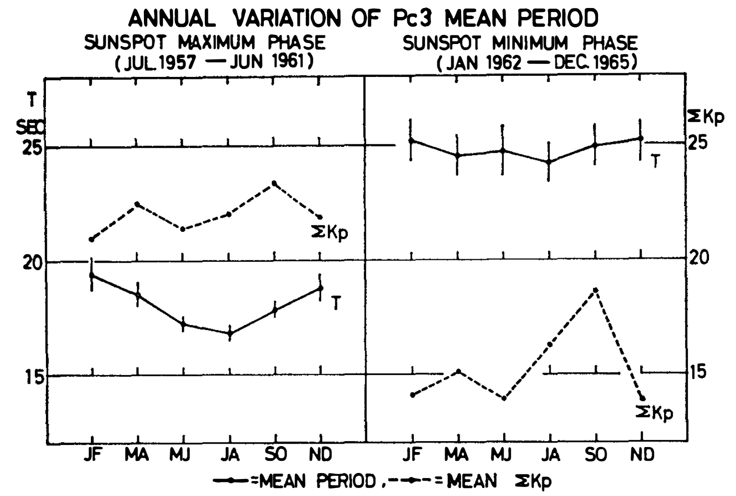

Fig. 4. Annual variations of period of Pc 3 and ΣKp for each of sunspot maximum and minimum phases.

and right frames correspond to the sunspot maximum and minimum phases, respectively. As the maximum and minimum phases, 48 months intervals from July 1957 to June 1961 and from January 1962 to December 1965 were selected. In the figure full and broken lines show the annual variations of the period and $\sum Kp$ averaged for each two months; January to February, March to April, and so on, for each of the phases. The period shows such a distinct annual variation as it becomes the shortest in the June solstice. Particularly, the variation is much clear in the sunspot maximum phase. In the maximum phase, the period which was about 17 sec in summer became about 19 sec in winter. At the present stage we do not have any model for such an annual variation of the period of Pc 3. On the other hand, $\sum Kp$ shows the well-known annual variation which has a maximum at each equinox in the analyzed two intervals. Therefore, it is difficult to attribute the annual variation of the period to the annual variation of the geomagnetic activity.

Recently, using the data obtained at Syowa Station, Antarctica, SAITO *et al.* (1979) have found similar annual changes in the periods of both Pc 4 and Pc 5 as that of Pc 3. According to their results, the periods of Pc 4 and Pc 5 become also shorter in summer than in winter. Such tendencies of the periods agree well with that of the period of Pc 3 in the present paper. Moreover, PARK *et al.* (1978) presented a distinct annual variation, which has a clear minimum around the summer solstice, of the electron density in the plasmasphere based on their whistler data Particularly, the variation was seen more distinctly in the sunspot maximum phase (1957–1962), but it was not so clear thereafter. A similar tendency is also seen in our results for the period of Pc 3

It seems that the annual variations of the periods of Pc 3, Pc 4 and Pc 5 and the variation of the electron density may be related closely with each other Such characteristic annual variations seem to be related to the state of the earth's rotational or magnetic axis against the sun rather than to the geomagnetic activity.

4. Diurnal Variation of Pc 3 Period

In the previous paper (KUWASHIMA *et al.*, 1979), we pointed out that only in summer of the sunspot maximum phase the daily variation of the period of Pc 3 showed clear "Inverted-U type", but in the other seasons of that phase and in each season of the minimum phase it was rather "U type". In Fig. 5 the daily variation which is represented by a contour map, of the period of Pc 3 observed at Memambetsu during the interval from January to March, 1976 is illustrated together with schematically cross-sectional plans of the plasmasphere on the equatorial plane. Left and right frames of the figure correspond to the geomagnetically quiet ($\sum Kp \leqq 11$) and disturbed

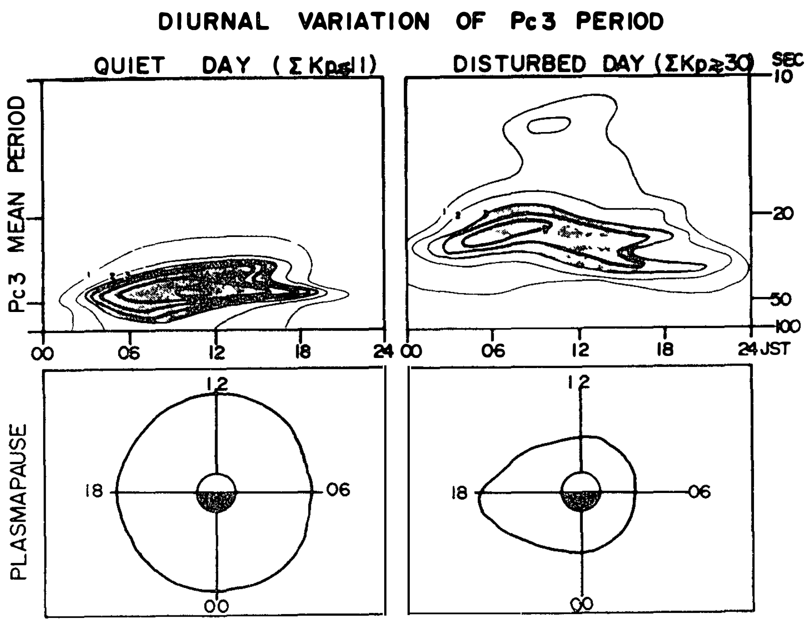

Fig 5. (Upper): Contour maps showing daily variations of period of Pc 3 at Memambetsu for both rather geomagnetically quiet ($\Sigma Kp \leqq 11$) and disturbed ($\Sigma Kp \geqq 30$) days from January to March, 1976
(Lower) Corresponding schematic pictures of the plasmasphere in the equatorial plane

($\sum Kp \geqq 30$) days, respectively. It should be noted in the figure that the average period for larger $\sum Kp$ days is much shorter than that for smaller days. In the quiet condition, occurrence peak of Pc 3 is seen just before noon and the period does not show any remarkable diurnal variation. While in the disturbed condition, the peak hours shift to the morning side and the period shows a distinct diurnal variation. This result coincides well with that by NAGATA and FUKUNISHI (1968). Moreover, the hourly averaged period of Pc 3 seems to show a rather "U type" variation. This result also corresponds to our previous one, because the analyzed interval is in the sunspot minimum phase. Looking at the variation in more detail, the period which was the shortest at about 8h increased gradually with the lapse of time and became the longest in the evening hours. We think that such a daily variation of the period represents one of the important characteristics of Pc 3 at low latitudes. Namely, the variation may reflect the state of the plasmasphere as shown in the lower frames of the figure. In other words, it is deduced that the variation of the period of Pc 3 may be also related to the size of the plasmasphere, because in the disturbed condition the plasmasphere may be compressed and the dawn-dusk asymmetry may occur.

5. Solar Cycle and Annual Variations of Pc 3 Occurrence

In Fig. 6 the solar cycle variation of the percentage occurrence of Pc 3 is shown together with those of both $\sum Kp$ and the relative sunspot number. The percentage occurrence means the ratio of the days on which Pc 3 occurs to the total days of the

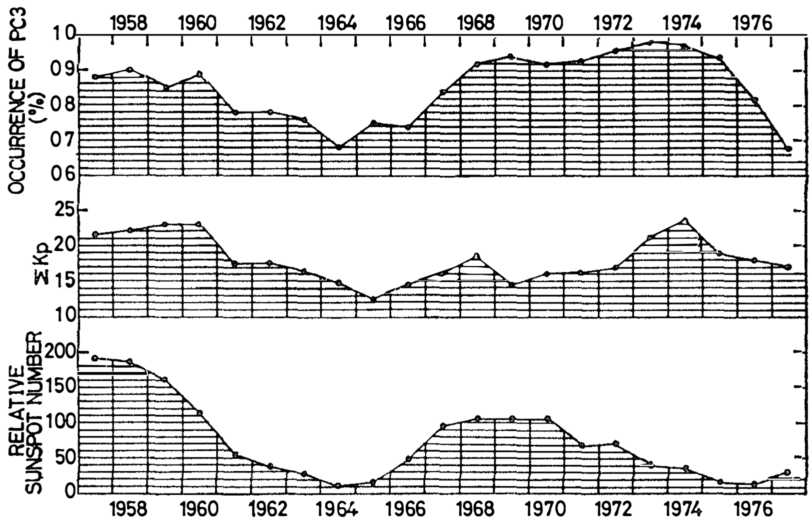

Fig. 6 Solar cycle variations of percentage occurrence of Pc 3 at Memambetsu, ΣKp and the relative sunspot number.

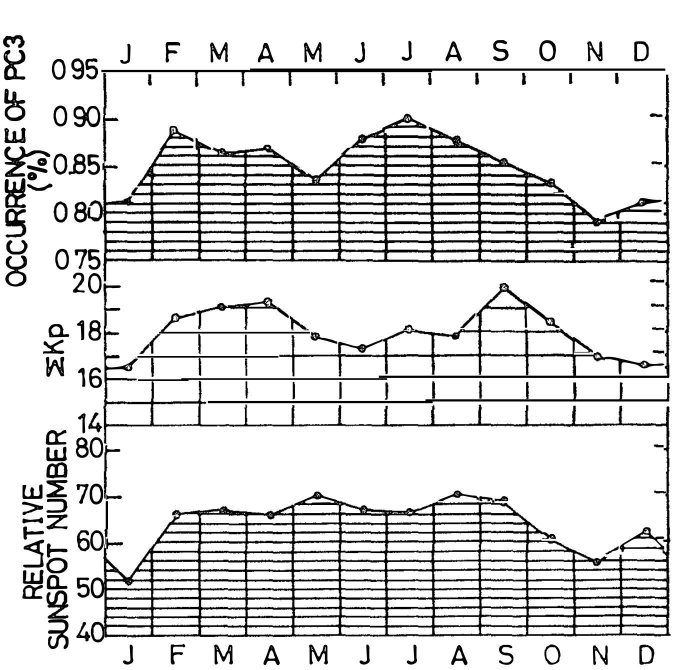

Fig. 7 Averaged annual variations of percentage occurrence of Pc 3 at Memambetsu, ΣKp and the relative sunspot number for twenty years from 1958 to 1977.

year. The occurrence also seems to show a solar cycle variation which corresponds well to those of $\sum Kp$ and the yearly averaged period (see Fig. 2). The annual variation, which was averaged for twenty years from 1958 to 1977, of similar percentage occurrence of Pc 3 observed at Memambetsu is illustrated in Fig. 7 together with those of $\sum Kp$ and the relative sunspot number. As shown in the figure, the variation of $\sum Kp$ has a clear maximum in each equinox, while that of Pc 3 occurrence seems to have maxima at the summer solstice and in the spring equinox. Namely, the annual variation of Pc 3 occurrence seems to depend not only on the geomagnetic activity but also on any other factor such as exemplified by SAITO (1964). Anyhow, it is very interesting that Pc 3 shows similar non-seasonal annual variations in both the period and the occurrence frequency.

6. Daily Variation of Pc 3 Occurrence

The averaged daily variation for years from 1957 to 1967 of occurrence frequency of Pc 3 is illustrated in Fig. 8 for each season. It should be noted that, as already described, Pc 3 is a typical daytime phenomenon which is observed very frequently at low latitudes and the occurrence peak is usually seen just before noon. Almost the same result for the interval from January 1976 to May 1978 is also given in Fig. 9 by a contour map. The contour is drawn every 0.2 step of monthly-hourly occurrence probability. The probability is calculated as follows: Firstly, each one-hour interval is divided into six 10-minutes ranges and the number of the intervals in which Pc 3 with longer duration than 30 minutes is observed at least over three 10-minutes ranges

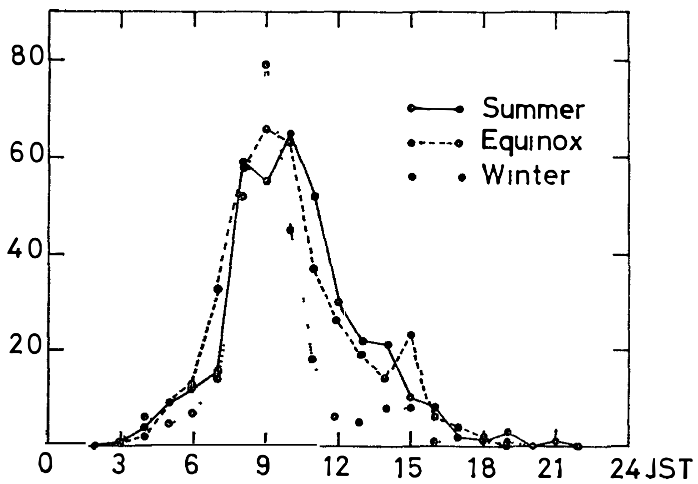

Fig. 8. Averaged daily variation of occurrence frequency of Pc 3 at Memambetsu for each season of eleven years from 1957 to 1967.

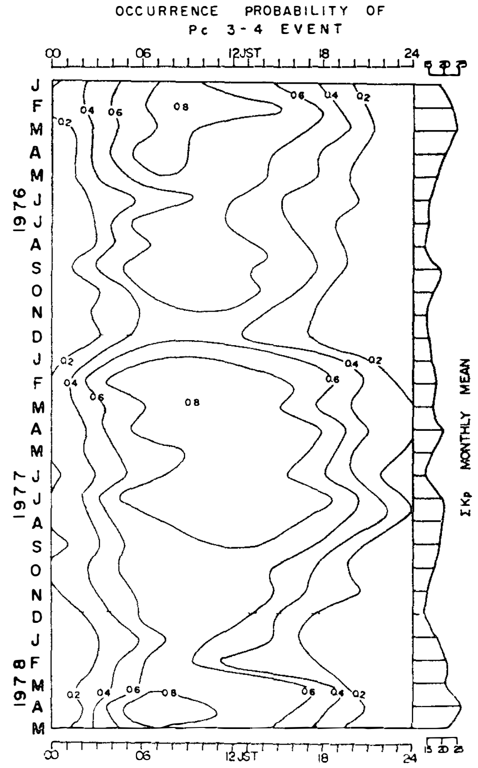

Fig 9 Contour map showing monthly ratio of occurrence of Pc 3 at Memambetsu for each hour of the day. Analyzed interval is from January 1976 to May 1978. Monthly average values of Kp are shown in the right frame of the figure

is counted for each hour of each month by hand-scaling from the continuous dynamic spectrum. The rate of the number to the total number of days of the month is defined as the monthly hourly occurrence probability. In the right side of the figure, monthly average $\sum Kp$ is shown. As shown in the figure, Pc 3 is usually active in the equinoctial months, but it seems to be related more closely to the geomagnetic activity.

7. Comparison of Pc 3 Characteristics between High and Low Latitudes

So far we described some characteristics of Pc 3 observed at low latitudes. However, for the purpose of more essential understanding of the pulsation, it will be necessary to compare the characteristics at low latitude with those observed at higher latitudes. The dynamic spectra of Pc 3-range pulsations observed at Memambetsu on 8 successive days from June 20th to 27th, 1977 are illustrated in the right frame of Fig. 10. This month was fairly quiet (monthly average $\sum Kp$ was 14.2), but the 8 days were more or less geomagnetically disturbed. Although Pc 3 events are observed very distinctly in the daytime of all the days, daily variations of the spectrum are not always identical with each other. It should be noted that on the first and fourth days which were rather magnetically disturbed, Pc 3 with a shorter period was enhanced. In the

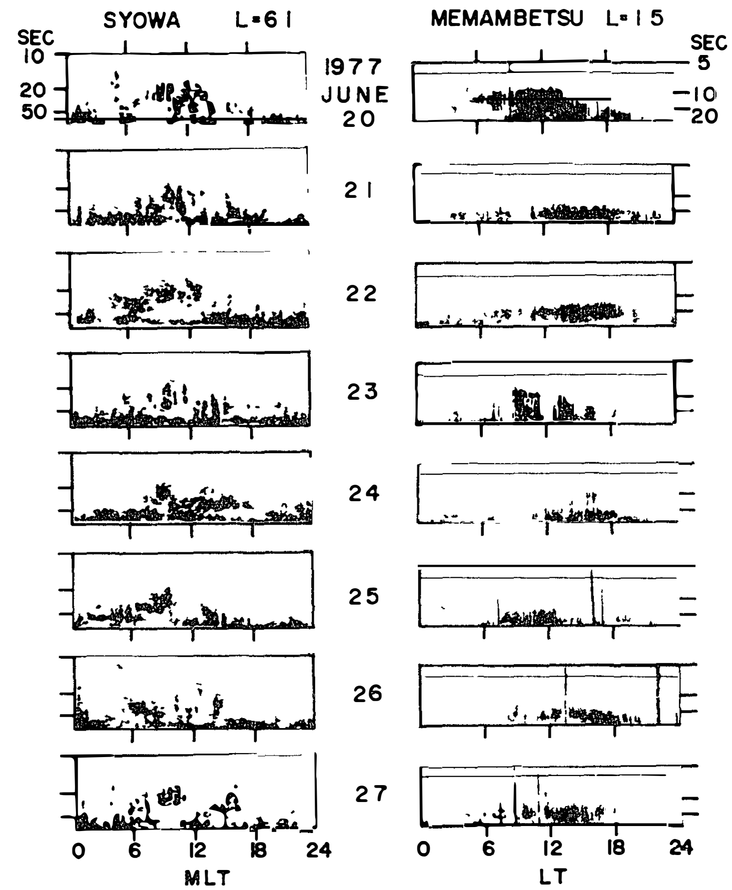

Fig 10. Dynamic spectra of Pc 3-range pulsations observed at Memambetsu (right frame) and at Syowa Station (left frame) on successive eight days from June 20th to 27th, 1977, in LT. The spectra at Syowa were presented by Dr. H. FUKUNISHI of the National Institute of Polar Research.

left frame of the figure, similar successive dynamic spectra of the pulsations observed at an auroral-zone station, Syowa, on almost the same days are given. The spectra were presented by Dr. FUKUNISHI of the National Institute of Polar Research. At the auroral station, not only active Pc 3 is seen clearly throughout the daytime of all the days, but also the daily variations of the spectra on the days are very similar with each other. Such a tendency at the high latitude station is apparently different from that at a low latitude station, Memambetsu. Namely, Pc 3 at low latitudes seems to be more complicated than that observed at high latitudes.

Next, dynamic spectra of Pc 3 observed simultaneously at Syowa Station and SANAE, Antarctica, on successive two days (Nov. 8th-9th, 1973) are shown in Fig. 11. The geographic and geomagnetic coordinates of these stations and the Hermanus Observatory are shown in Table 1. Syowa Station and Hermanus are located along almost the same geomagnetic meridian of about 80° in longitude. The longitude of

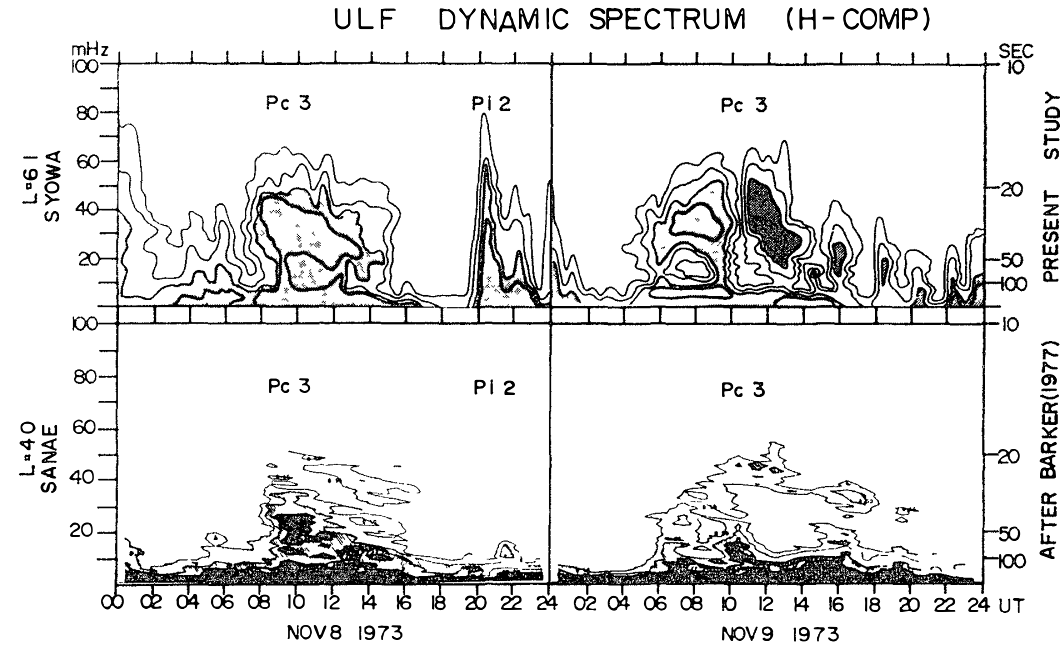

Fig. 11. Dynamic spectra of Pc 3 observed simultaneously at Syowa Station (Upper) and at SANAE (Lower) on November 8th and 9th, 1973. The data from SANAE were presented by Dr. M. D. BARKER of the Natal University of South Africa.

SANAE is somewhat different from those of the above two stations, but in the present study we include SANAE in the Syowa chain, because near the Syowa Station-Hermanus meridian the station is the most appropriate one to examine the effect of the plasmapause in relation to the occurrence of Pc 3. Namely, L-values are 6.1 at Syowa Station and 4.0 at SANAE, respectively. At these two stations a very similar daily variation of the spectrum was observed on each of the days. Magnetic local time at Syowa

Table 1. Geographic and geomagnetic coordinates of Syowa chain-stations

Stations	Geographic		Geomagnetic	
	Latitude	Longitude	Latitude	Longitude
Syowa Station	−69.0°	39.6°	−70.0°	79.2°
SANAE	−70.3	353.8	−63.4	42.6
Hermanus	−34.4	19.2	−33.6	81.6

Station is almost equal to UT. On Nov. 8th, Pc 3 with shorter period components was activated suddenly at about 08h UT and continued until about 16h UT at both two stations. At each station, the period of Pc 3 was the shortest at about 08h and increased in course of time. The longest period was observed at about 14h. On the next day, Pc 3 was enhanced at about 06h. And the daily course of the averaged period

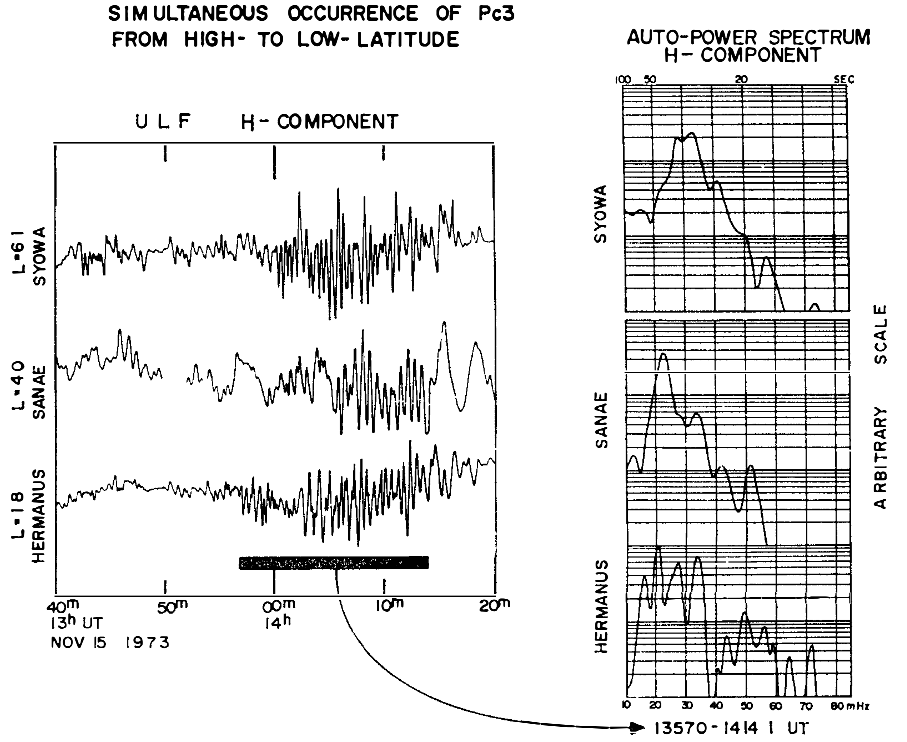

Fig. 12. (Left) Wave forms of Pc 3-range pulsations observed simultaneously at Syowa meridian-chain stations, Syowa Station, SANAE and Hermanus. Data from the latter two stations were presented by Dr. M. D. Barker and the Hermanus Magnetic Observatory, respectively. (Right) Autopower spectra of horizontal components of the pulsations.

was very similar at the stations. These characteristics are just consistent with those observed at low latitudes as shown in Fig. 5. Namely, the period of Pc 3 is the shortest in the morning hours at the auroral and plasmapause stations. Wave trains of the pulsations observed simultaneously at Syowa meridian-chain stations, Syowa Station (L=6.1), SANAE (L=4.0) and Hermanus (L=1.8), are compared with each other in the left frame of Fig. 12. Firstly, it should be noted that Pc 3 is observed almost simultaneously at the chain stations with a wide latitudinal range. In the figure, Pc 3 is no doubt activated simultaneously at the stations during the interval from 1357 to 1416 UT. Nevertheless, the waveforms are not so similar.

Moreover, in order to clarify in more detail the difference between the waveforms of the pulsations observed simultaneously at these stations, power spectra of the horizontal component of the pulsations in a marked interval from 1357.0 to 1414.1 UT are calculated and are compared with each other. The results are shown in the right frame of the figure. It is very remarkable in the figure that the period of Pc 3 observed in the auroral region (Syowa Station) is distinctly shorter than that observed near the plasmapause (SANAE), though the appearances of the spectral characteristics of the pulsation are fairly similar. While at the low latitude station, Hermanus, the spectral characteristics are very complicated and different from those at higher latitudes. Namely, at Hermanus various kinds of spectral component are contained in the wave train. In future investigation of this problem, it will be necessary to gather and analyze much simultaneous data from stations over a wide range, latitudinally and longitudinally. Anyhow, we are very interested in the clear latitudinal dependence of the period components of Pc 3, because the fact seems to give an important information connected with the character of the resonator of the pulsation in the magnetosphere.

8. Concluding Remarks

In the present paper, we investigated firstly the solar cycle, annual and daily variations of the averaged period and the occurrence frequency of Pc 3 observed at the most representative station, Memambetsu, of our Japanese station-chain, mainly statistically. Data obtained for the long interval from the IGY to the present IMS were analyzed, and some interesting results have been obtained. Namely, the variations of both occurrence frequency and period of Pc 3 may be related closely to those of solar and geomagnetic activities Particularly, it should be emphasized that the variations of period are well interpreted as the change in the size of the plasmasphere. Next, we compared the variations with those at higher latitudes on the dynamic spectrum. And we showed that Pc 3 occurs usually in a wide latitudinal range but its period components contained in the wave are clearly different by the latitude In the near future, we will investigate the problem more statistically and quantitatively.

Acknowledgments

The authors wish to thank Professor T SAITO of Tohoku University and Dr. H. FUKUNISHI of the National Institute of Polar Research for their kind advice and valuable discussions. The authors also thank sincerely Dr. BARKER of the Natal University and the Director of the Hermanus Magnetic Observatory for their kind presentations of data at SANAE and Hermanus, respectively.

References

IWABUCHI, M , FUJII, R. and UTSUMI, T (1978): Gurafiiku-dispurei o mochiita kaiwagata supekutoru kaiseki shisutemu (Conversational system of spectrum analysis by the use of graphic display) Nankyoku Shiryô (Antarct Rec), **62**, 29–70

KAWAMURA, M (1976): Geomagnetic and geoelectric observations Rep Geomagn Geoelectr. Obs (Rapid Var.), Kakioka Magn Obs , **17**, i–iv.

KAWAMURA, M. (1977): Geomagnetic and geoelectric observations. Rep. Geomagn. Geoelectr. Obs. (Rapid Var.), Kakioka Magn. Obs., **18**, i–iii.

KAWAMURA, M. and KUWASHIMA, M. (1977): On the geomagnetic pulsation Pc (Part II), Middle- and low-latitude Pc 3. Mem. Kakioka Magn. Obs., **17** (1), 7–18.

KUWASHIMA, M., SANO, Y. and KAWAMURA, M. (1979): On the geomagnetic pulsation Pc (Part III), Spectral and polarization characteristics of middle- and low-latitude Pc 3. Mem. Kakioka Magn. Obs., **18** (1), 1–28.

NAGATA, T. and FUKUNISHI, H. (1968): Dependence on geomagnetic activity of magnetic pulsation frequency of Pc 3 and Pc 4 ranges. Geophys. J. R. Astron. Soc., **15**, 69–78.

PARK, C. G., CARPENTER, D. L. and WIGGIN, D. B. (1978): Electron density in the plasmasphere, Whistler data on solar cycle, annual and diurnal variations. J. Geophys. Res., **83**, 3137–3144.

ROMAÑÁ, A. (1960): Transactions of the Toronto Meeting, September 3–14, 1957, Part IV-special report, Report of the committee on rapid variations and earth currents. IAGA Bulletin, **16**, 318–347.

SAITO, T. (1964): Mechanisms of geomagnetic continuous pulsations and physical states of the exosphere. J. Geomagn. Geoelectr, **16**, 115–151.

SAITO, T., SAKURAI, T. and TAMURA, T. (1977): High-speed spectral analysis (HISSA) ho ni yoru jikiken jyôran no kenkyû (Study of magnetospheric disturbances by high-speed spectral analysis (HISSA) method). IMS Symposium Hokoku, 1977 (Report on the IMS Symposium, 1977), 111–121.

SAITO, T., YUMOTO, K. and TAMURA, T. (1979); Syowa Kiti ni okeru Pc 5 no shuki henka ni tsuite (On the variations of period of Pc 5 at Syowa Station). Dai-2-kai Kyokuiki ni okeru Denriken-Jikiken Sogo Kansoku Shinpojiumu (The Second Symposium on Coordinated Observations of the Ionosphere and the Magnetosphere in the Polar Regions), Held from February 14th to 16th, 1979, at the National Institute of Polar Research.

YOSHIMATSU, T. (1960): Geomagnetic and geoelectric observations during the International Geophysical Year. Rep. Geomagn Geoelectr. Obs. IGY. 1957–58, Kakioka Magn. Obs., i–viii.

(*Received May 25, 1979*)