Geomagnetic Pulsations in Middle Latitudes
—— Morphology and Its Interpretation ——

By

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概　要

脈動という名のもとに包括される短周期現象には種々の形態のものがあり，中低緯度において観測されるものに対して pt，pc という一応の分類が行われているが，これ等は代表的なものであつても観測される脈動全部を十分にいいつくすことは出来ない。又観測の條件例えば器械の特性，観測の時期等が結果に与える影響も重視しなければならない。この点も考慮し pt，pc の一応の分類から出発して典型的形態特性を求め，それ等の差異に従つて再分類又は新分類を進めそれによる特性群を求める。このようにして合理的な分類とそのおのおのに対する特性を記述することができた。例えば日変化，季節変化，年々変化等もそれぞれについて固有のものをうることができる。

又この過程において脈動の活動度と地磁気擾乱との関係が脈動の各種類に応じて求められた。あるいは地磁気擾乱の種類と強度に応じて観測される脈動の種類が違つて来るともいうことが出来る。脈動の世界時日変化に関連して地磁気活動度のスパイラルパターンを調査したが従来いわれている観測結果と称するものについては疑問の点が多い。しかしKインデツクスについて調べた所では少し違つてはいるが一応スパイラル状の極大地域がみられた。脈動の世界時日変化もこの点と同様にして考えることが出来る。

各種類の脈動の多くの特性を現象論的に相互間又は他の地磁気擾乱等との相互関係において説明することは可能であるが，その生因を物理的に解明するにはなお多くの困難が存在している。今は一応外圏大気内の電磁流体力学的現象として説明を試みた。地表上 3000 粁位の所にあると考えられるアルフベン波速度の極大地域を境としてそれより下部においてはやゝ安定な振動が成立しそれが周期 20 秒程度の定常的振動に相当する。又外圏大気全体の不安定な振動がもつと周期の長い減衰状振動に対応する。前者の典型的出現が pc であり後者のそれは pt である。

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Chapter 1 Preliminaries

§ 1.1 Introduction

In the long history of observation and investigation of pulsations which began at the age of B. Stewart (1861), many excellent papers have been published. In the early stage of investigation the works on this field were made by M. Eschenhagen (1897), W. van Bemmelen who gave the name "pulsation" (1902), Th. Arendt (1896), G. Angenheister (1920), B. Rolf (1931), L. Harang (1932), E. Sucksdorff (1936) and F. Lubiger (1935). In Japan, such studies were worked out before 1950 by T. Terada (1917), H. Hatakeyama (1934), M. Hirayama (1934), T. Yoshimatsu (1933), S. Imamiti (1948), and Y. Kato and his colleagues (1949).

However investigations before about 1950 had given often ambiguous or contradictious results which must be caused by many origins. Such ambiguity or contradiction is partly due to the criteria by which "pulsations" in subject are picked up. It has become gradually clear from about 1950 that "pulsations" can be classified into many groups, at least three groups, having different character. If we pick up both the so-called "night pulsation" and "day pulsation", statistical results on diurnal variation of occurrence frequency of such "pulsations" may become very ambiguous. Then, the classification is one of the most important processes for the investigation of pulsations.

Next cause of ambiguity or contradiction in the results of research on pulsations, especially in statistical results, may be due to the fact that many features of pulsations vary in the period of 11 years according to the solar activity. Since it is very difficult that researches of pulsations are made on the data of quick-run recording continued longer than 11-years, many results of investigations have been given generally from the data from one or two years observations. Such results on character of pulsations have a meaning under the restricted condition only that they can be applicable to the phenomena in the period of the corresponding level of solar activity.

The activity of the so-called "night pulsations", pt, was minimum in the International Geophysical Year, 1957—1958, because the IGY coincided with the period of maximum solar activity. And the relative activity of the "night pulsations" to that of "day pulsations" was also minimum.

In the following chapters, it will be carefully taken into consideration that features of pulsations vary in the 11-year period according to the change of the solar activty.

Different methods of observation are the third origin of the ambiguity or contradiction. Pulsations are generally observed by one of the following three recordings,

(i) Direct recording of magnetic elements, with high sensitivity variometer and quick-run recorder (magnetograph).

(ii) Earth-currents recording (tellurigraph).

(iii) Recording of time derivative of magnetic elements (induction magnetograph).

Their frequency responses are different each other and the amplitude ratio in observation of sinusoidal oscillation having period T is about $1 : 1/\sqrt{T} : 1/T$. Then, it is very difficult to compare the observed results each other without careful consideration on this frequency response. For example, it is obvious that the occurrence frequency of the periods seriously depends upon the frequency response of observing apparatus. It is often experienced in the survey of record that the oscillation form of pulsations on induction magnetograms is quite different with that on magnetograms (direct recording of magnetic elements).

In the following sections of this chapter, preliminary considerations of the above said points, classification and observing method, will be given to avoid any confusion of the results given in this paper. On the other hand, considerations of inequality in the 11-year period due to the change of the solar activity will be introduced in the section of the following chapters when they are required.

§ 1.2 Preliminary classification of pulsations

For the complete classification of pulsations their characters should be given clearly. On the other hand, classification is essential to investigation of pulsations as it is said in the introduction. Then, such a method as successive approximation is required in this respect. First approximation of classification will be considered in this section. Further approximation will be given in the chapter 3.

As regards high latitude pulsations, giant pulsations have been distinguished in relatively clear conception because of their restricted spatial distribution. Recently from the observation of pulsations in middle or low latitudes, many authors have concluded that two groups of different characters are found in those pulsations. (E. R. R. Holmberg 1953, V. A. Troitskaya 1953, G. Angenheister 1954, J. G. Scholte and J. Veldkamp 1955, K. Yanagihara 1956, 1957 and Y. Kato and others 1956, 1957). Pulsations of a group occur frequently in the night time and often precede to or accompany a bay disturbances. They are called sometimes "night pulsations" or "burst oscillations". On the other hand, pulsations of the other group are found often in the daytime, and called "day pulsations". Day pulsations continue often during many hours as quasi-sinusoidal oscillations.

These coincident opinions are introduced in the resolution at the Meeting of the Committee on Rapid Magnetic Variation and Earth Currents of IAGA, IUGG, held at Copenhagen during April 9-11, 1957, and the symbols pt and pc are given for these two groups of pulsations with the following definitions.

pt : A phenomenon consisting of several series of oscillations, each series lasting generally 10 to 20 minutes, the whole phenomenon lasting for periods of not more than about one hour.

pc : Pulsations having a considerable element of continuity, having periods between 10 and 40 seconds, lasting a number of hours.

Some typical examples of pt and pc are shown in Fig. 1

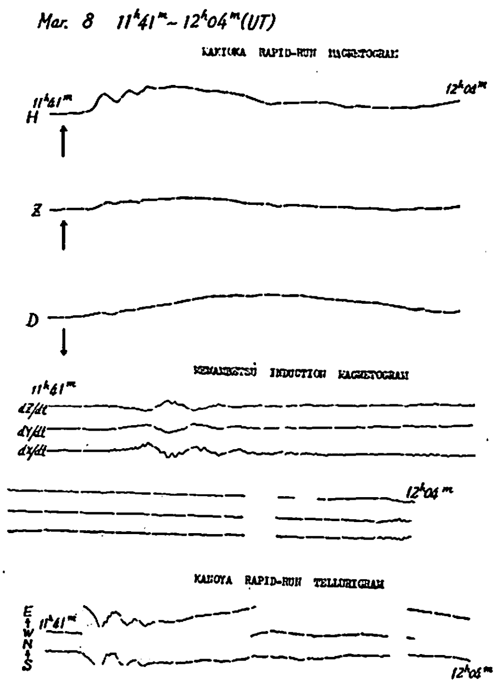


Fig. 1. (a_1) Examples of pulsation pt.

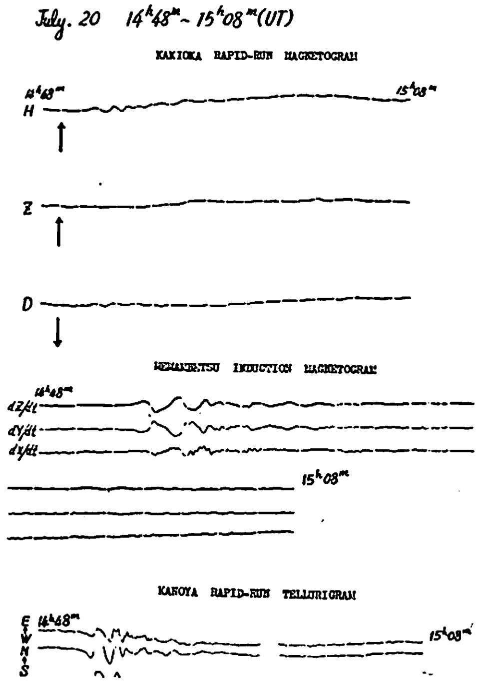


Fig. 1. (a_2) Examples of pulsation pt.

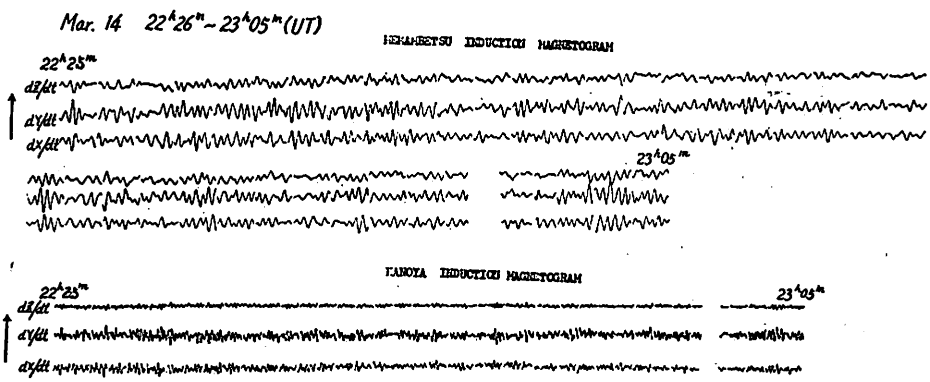


Fig. 1. (b) Examples of pulsation pc.

Because of the inevitable ambiguity of description of phenomenon it may be possible that some observers faithful to the description in the resolution may miss-understand the classification of pulsations. Necessity of this consideration is shown in the fact that the stations having maximum occurrence frequency of pt in night time and those having that in daytime are co-existing in such a restricted area as Europe. In Fig. 2, the hourly occurrence frequency of pt counted from the data in the report prepared quarterly by the Committee on Rapid Magnetic Variation and

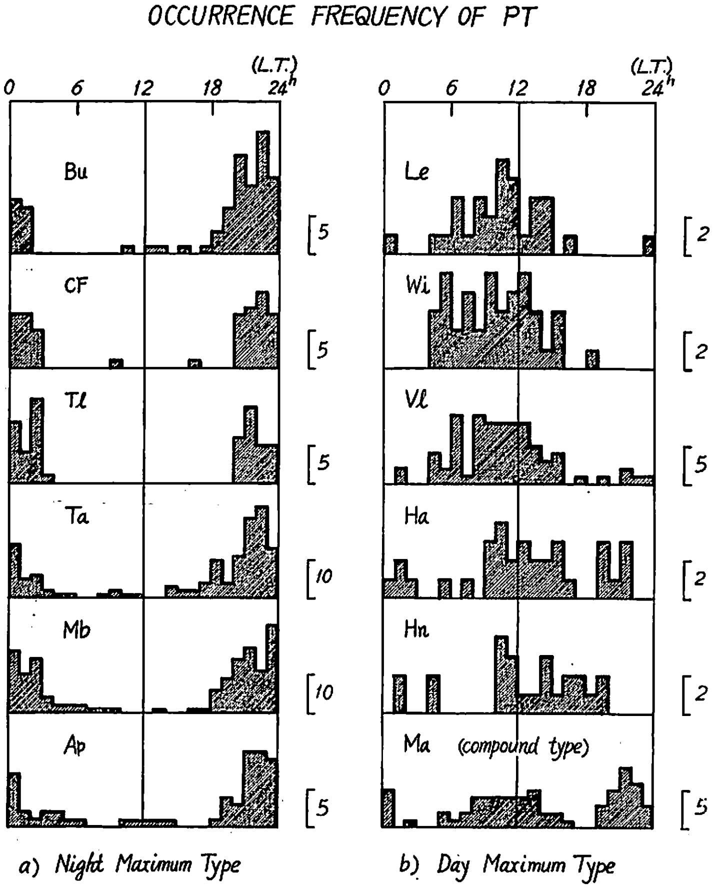


Fig. 2. Hourly occurrence frequency of pt counted from the data reported in the three-monthly list of the IAGA.

Earth Currents of IAGA is presented for the stations listed in Table 1. Two modes of diurnal variation are found in this figure. One is the night maximum mode and the other is daytime maximum mode. In the area, Europe and Africa, both the two modes of diurnal variation can be found together. According to our opinion which will be given in the following chapters the diurnal variation of occurrence

Table 1.

Abbreviation	Station	Geographic latitude	Geographic longitude
Le	Lerwick	+60°08′	358°49′
Wi	Witteveen	+52°49′	6°40′
Vl	Valentia	+51°56′	349°15′
Ha	Hartland	+51°00′	355°30′
Ma	Manhay	+50°18′	5°41′
Bu	Budkov	+49°04′	14°01′
CF	Cambon-la-Forêt	+48°01′	2°16′
Mb	Memambetsu	+43°55′	144°12′
Tl	Toledo	+39°53′	355°57′
Ta	Tamanrasset	+22°48′	5°31′
Hn	Hollandia	−02°30′	140°30′
Ap	Apia	−13°48′	188°14′

frequency of pt must have the mode of night maximum, then the "pt" picked up at the stations having daytime maximum mode is different from generally accepted pt. Or, at least, it differs from the examples presented in the Provisional Atlas prepared preliminarily by the Committee.

The above confusion may arise from the difference in the observing apparatus at first. And the second cause is that the International Geophysical Year is the period of maximum solar activity when occurrence frequency of pt is minimum as shown in the later section. There are some conditions in which the selection of pt is rather difficult for relative low activity to the other fluctuations such as pc. Some characters of our pt useful to select it are given as follows :

(1) They often precede to or accompany bays or bay-like disturbances.

(2) They often begin rather suddenly, and then it is almost possible that their beginning times are determined within the error of a minute or less.

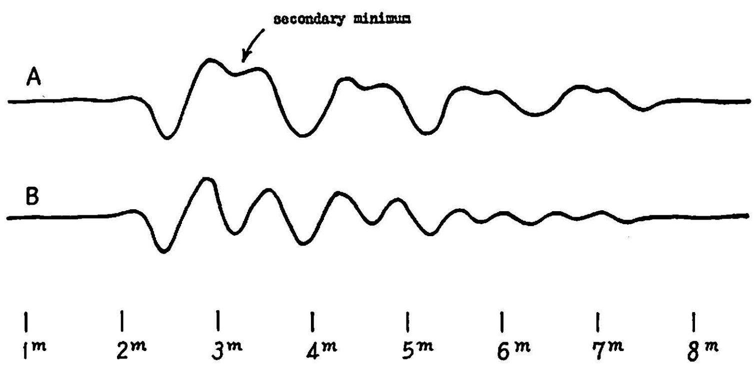


Fig. 3 Peculiar form of oscillation of pt.

(3) Generally they consist from several isolated series which are damped oscillations.

(4) Their form of oscillation is not so regular as pc, but some general forms such as series of pulses in the upper part of Fig. 3 are often found. The observed form of fluctuation mostly depends on frequency response of apparatus, of course. The diagrammatic example in Fig. 3 is a suitable one for the record by induction magnetograph. The similar form of the example is found in the Provisional Atlas.

§ 1.3 Method of observation

The data of pulsations are generally taken from the quick-run magnetogram, induduction magnetogram or tellurigram as shown already in § 1.1. It is most desirable to directly measure the three components of the magnetic field, but studies of short period pulsations are rather difficult by direct record of magnetic elements because of overlapping large amplitude fluctuations with longer period. Then, in the present stage of investigation, induction magnetograms and tellurigrams also supply often useful data for study of pulsations. For example, the pulsations with period less than 10 sec discussed in chapter 3 is hardly observed by direct recording of

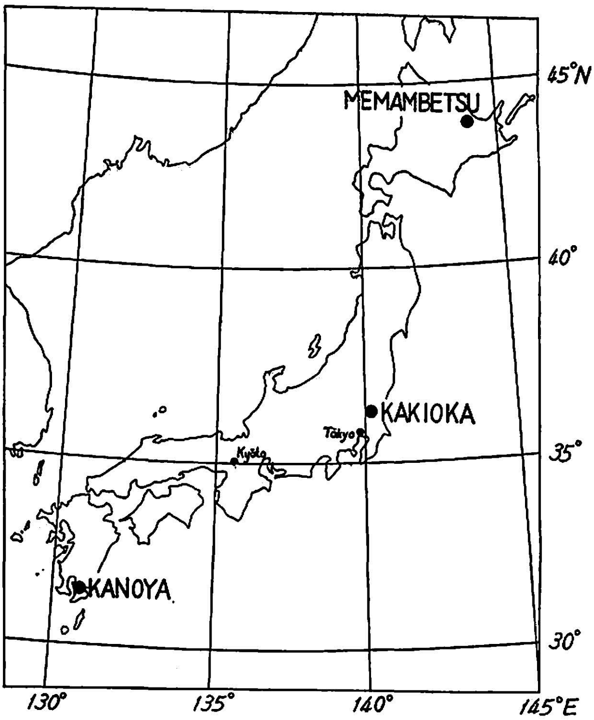


Fig. 4.

the magnetic elements.

The amplitude of sinusoidal oscillations with period T on induction magnetograms is proportional by the ratio 1/T to that on magnetograms of direct measurment. The amplitude of oscillation on tellurigram is different for each case of its vector direction for the anisotropy and spacial distribution of electric conductivity of the earth, but in the mean state its ratio to amplitude of magnetic field is $1/\sqrt{T}$ (H. Hatakeyama 1938).

When the period of fluctuation becomes short and near the proper period T_0 of the measuring apparatus, its sensitivity becomes low rapidly. Curves of sensitivity vs period for the high sensitivity quick-run magnetograph at Kakioka (36°14′N, 140°11′E), the induction magnetographs by loop at Memambetsu (43°55′N, 144°12′E) and Kanoya (31°25′N, 130°53′E) and the high sensitivity quick-run tellurigraph at Kakioka, data from which are often used in the following chapters, have been given by M. Hirayama and K. Kurusu and reproduced here in Fig. 5. The investigation of pulsations stands in need of the consideration of frequency response measuring apparatus, since there is obviously distinct difference of frequency response. It is often heard that the experienced observer in the survey of magnetogram (direct record of magnetic element) is astonished at the different aspect of induction magnetogram, and vice versa.

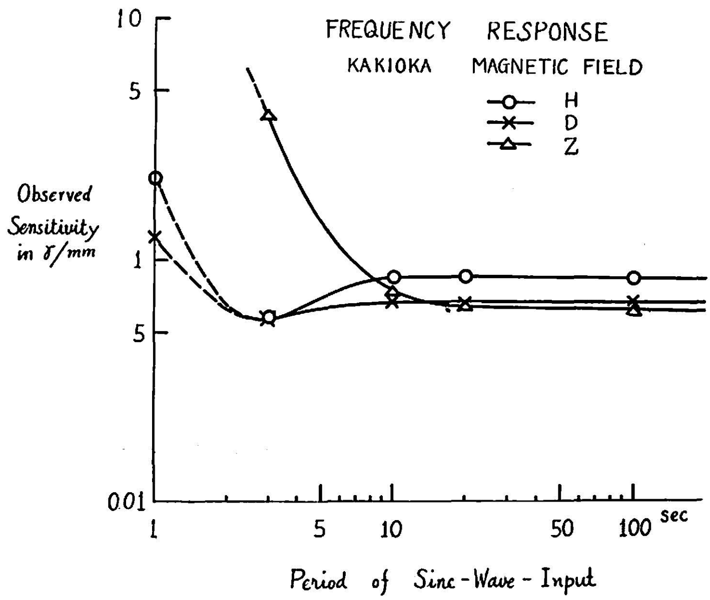


Fig. 5. (a) Sensitivities of the quick-run magnetograph at Kakioka.

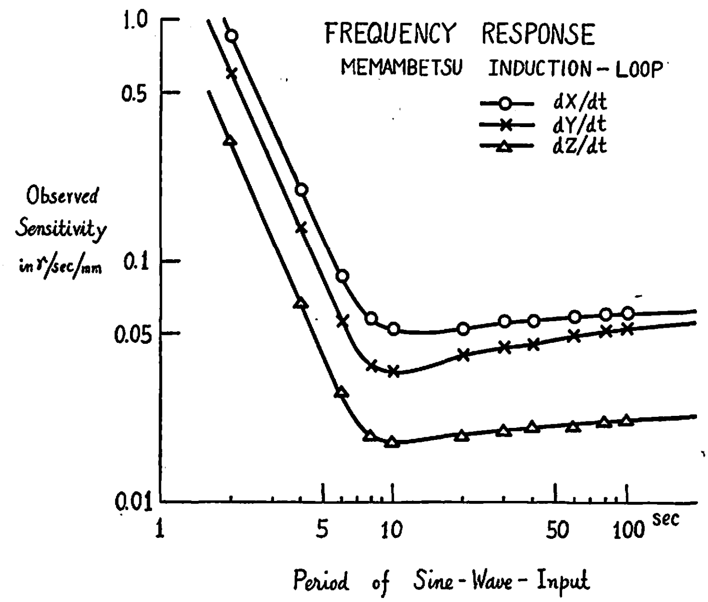


Fig. 5. (b) Sensitivities of the induction magnetograph at Memambetsu.

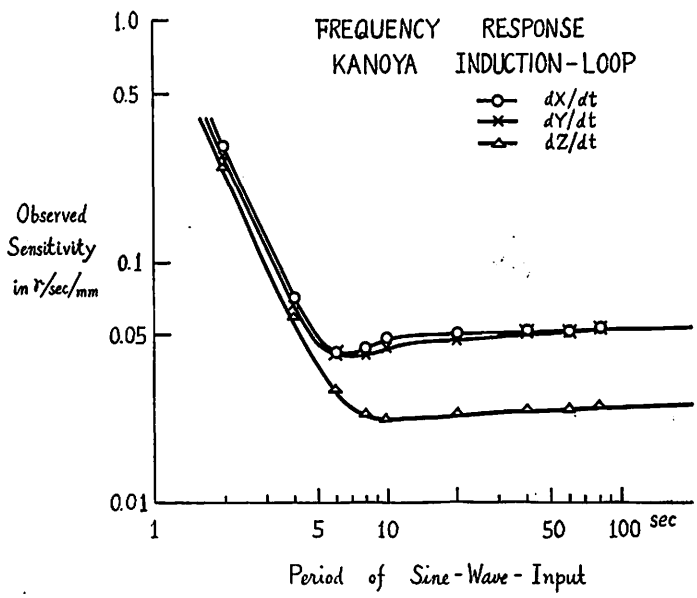


Fig. 5. (c) Sensitivities of the induction magnetograph at Kanoya.

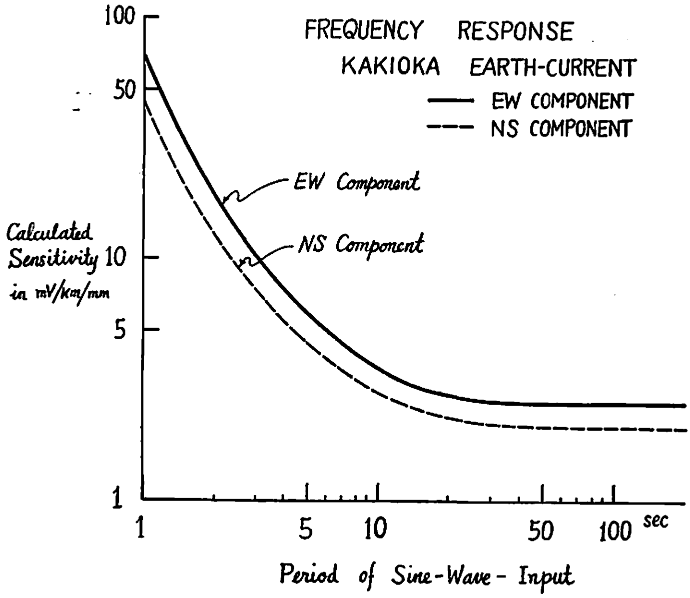


Fig. 5. (d) Sensitivities of the quick-run tellurigraph at Kakioka.

Chapter 2 Variation of pt

§ 2. 1 Diurnal variation

The maximum occurrence of pt is considered to lie essentially in night hours irrespective of the apparrent two modes of diurnal variation in Fig. 2 of Chapter 1. The hourly occurrence frequency of pt averaged over about two sunspot cycles has been given by K. Yanagihara (1957a), and it is reproduced here in Fig. 6. This curve is obtained from the ordinary tellurigrams at Kakioka for 20 years, 1934–1953. As it is expected, the hourly occurrence frequency is very high in night hours and its maximum is found near but slightly before the local midnight. The slight earlier occurrence of maximum frequency than the local midnight is found also in the result by Y. Kato et al (1956) using the induction magnetogram at Onagawa (38°26′N, 141° 28′E), (Fig. 7). The period of their data is the sunspot minimum year. Since the occurrence of pt in the sunspot minimum period is about four or five times as frequent as that in the sunspot maximum period, the diurnal variation of occurrence frequency in the sunspot minimum period is not so different from the averaged one. The diurnal variation of occurrence frequency in the sunspot maximum period, on the other hand, is not the same, but little modification is found. Fig. 8 shows the hourly occurrence frequency of pt for the year 1958 observed at Memambetsu by the induction magnetograph. The noticeable double maxima at 21. 5h and 24h LT

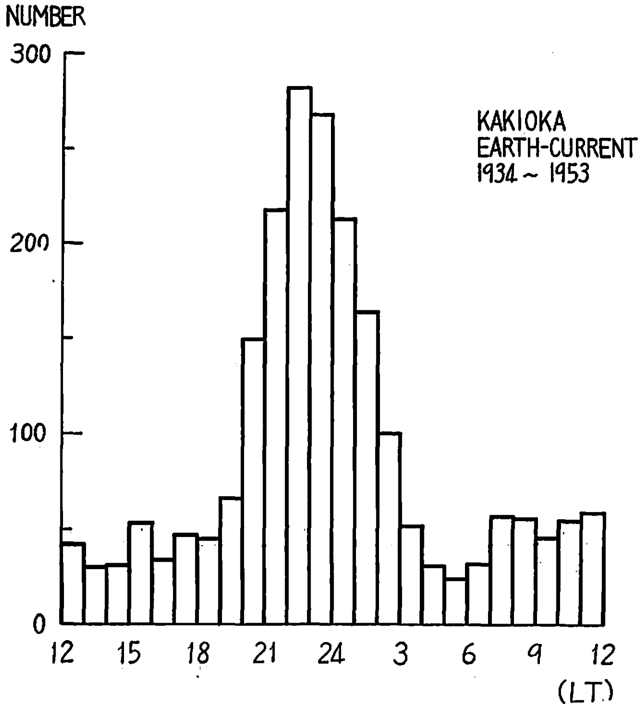


Fig. 6. Hourly occurrence frequency of pt averaged over 20 years, at Kakioka.

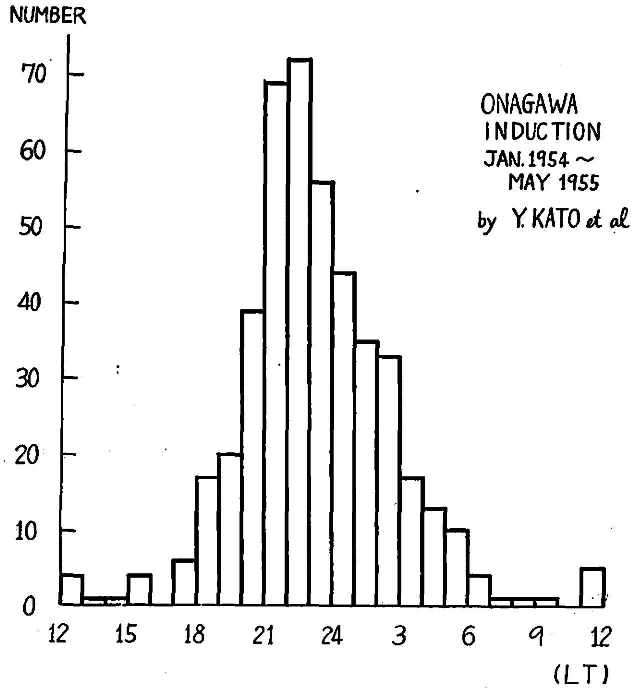


Fig. 7. Hourly occurrence frequency of pt observed at Onagawa in the sunspot minimum year (after Y. Kato, J. Ossaka, T. Watanabe, M. Okuda and T. Tamao 1956)

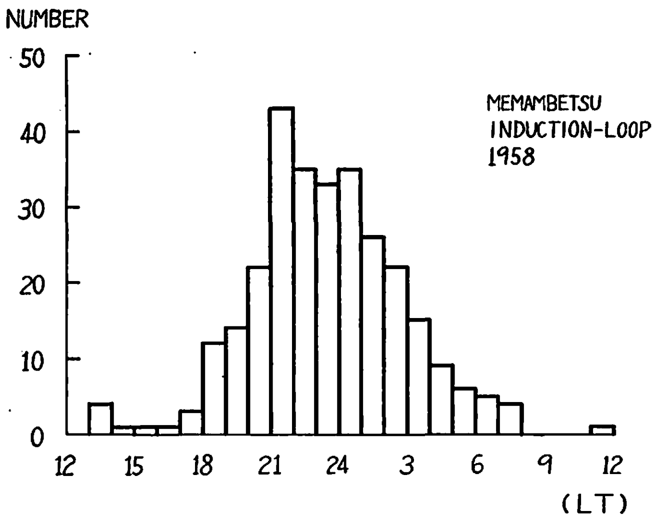


Fig. 8. Hourly occurrence frequency of pt observed at Memambetsu in the year 1958.

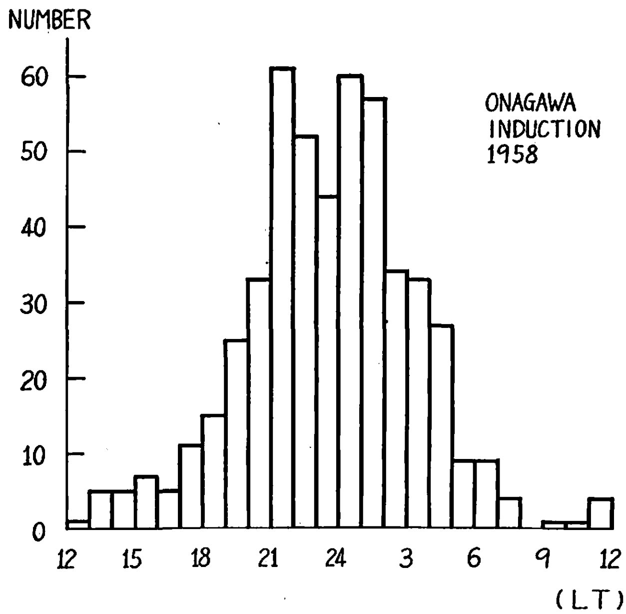


Fig. 9. Hourly occurrence frequency of pt in the year 1958 counted from the Monthly Reports of the Onagawa Magnetic Observatory.

are found in the figure. The appearance of double maxima is also ascertained by the data at Onagawa. The hourly occurrence frequency of pt for the year 1958 at Onagawa is counted from the list of the individual series of pt in the Monthly

Report, and it is presented in Fig. 9. It is interesting that the diurnal variation observed at the European station clearly shows also the double maxima or broaden maximum irrespective of the period of observation (Fig. 10). The differences in the time of maximum occurrence frequency for the stations of different longitudes will be discussed in the next section.

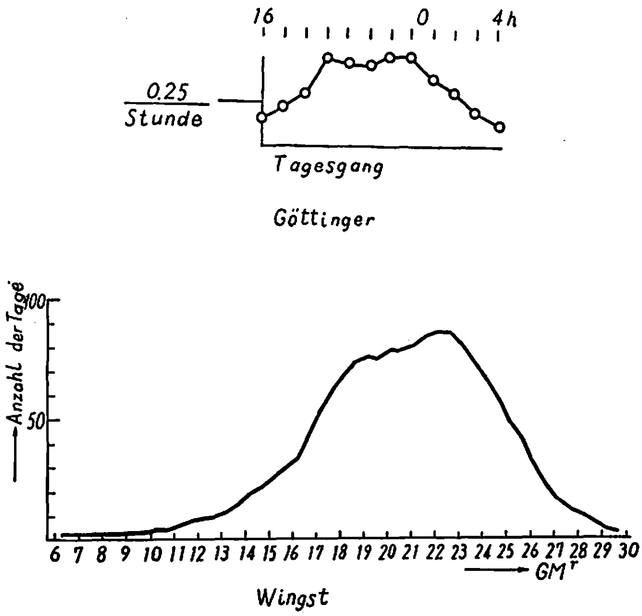


Fig. 10. Diurnal variations of occurrence frequency of pt at Göttingen (after G. Angenheister, 1954) and Wingst (after H. Theis 1957, Über erdmagnetische Pulsationen, Ergänzungsheft Reihe A (8°), Nr. 4 zur Deutschen Hydrographischen Zeitschrift).

Setting apart the problem of detailed character, the interpretation of general tendency of occurrence of frequency maximum in night time has been approached theoretically in several ways. The shielding effect by the ionosphere was discussed firstly by A. A. Ashour and A. T. Price (1948) for the cause of diurnal inequality of occurrence frequency of pulsation, and it was extended and applied to pt by Y. Kato and T. Watanabe (1956). But some objections arose at once (K. Yanagihara 1957c), and again why the shielding effects operate more severely upon pt than pc having generally shorter period is not clear also. More recently studies by one of them show that the ionospheric shielding is not effective for the oscillations having the such period as pt (T. Watanabe, 1958). On the other hand, it is natural to consider that the diurnal variation of occurrence frequency of pt depends partly upon the daily behaviour of geomagnetic disturbance or at least, that of some kinds of disturbance, since the occurrence of pt is closely connected to geomagnetic bays or bay-like disturbances and the occurrence rate is proportional to geomagnetic activity index K (K. Yanagihara 1957 b). H. C. Silsbee and E. H. Vestine (1942) gave the hourly distributions of occurrence frequency of positive and negative bays in the polar cap, auroral zone, middle latitudes and low latitudes. In all the regions except the polar cap, the occurrence of bay is more frequent in night hours than in day times.

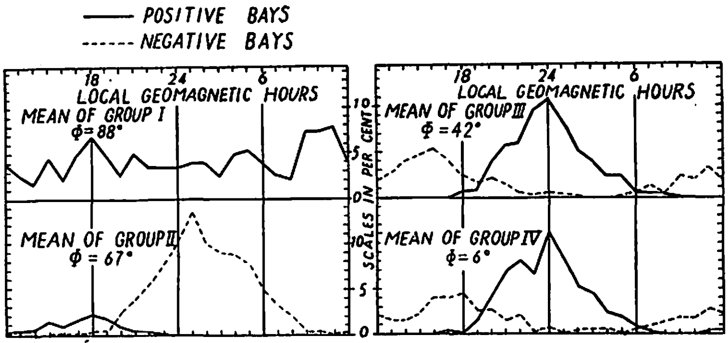


Fig. 11. Hourly occurrence frequency of positive and negative bays in the polar cap, auroral zone, middle latitude and the low latitude, after H. C. Silsbee and E. H. Vestine, 1942.

Especially in the auroral zone the number of negative bays is 9 times as large as that of positive bays, and this frequent occurrence of bays in night hours is significant in connection with diurnal inequality of occurrence frequency of pt. Though some suggestive researches have been presented as regards the local time control in activity of some kinds of geomagnetic disturbances containing bays, any sufficient interpretation has been not given as yet. Some authors have considered that the Störmer-like impinging of the solar particles upon the earth causes the observed space- and time-distributions of geomagnetic activities. (J. H. Meek 1955, E. R. Hope 1956, A. P. Nikolski 1956, 1957) In this connection, further discussions will be given in the next chapter.

Recently, the existence of high energy particle zones, Van Allen Bands, in the outer atmosphere was found by the artificial satellite, and its connection to the origin of aurorae or geomgnetic bays has been discussed. Studies of its local time control are desirable.

That occurrence frequency of pt is controled by the geomagnetic activity only is denied by the fact that yearly occurrence frequency is inversely proportional to the solar activity as it is shown in § 2. 4. From the standpoint that the origin of pt is a hydromagnetic phenomenon in the outer atmosphere, obstructing activity of that region (not of the ionosphere) may control occurrence frequency of pt. Diurnal variations and the 11-year variation are influenced severely by this control, which will be discussed in detail in § 5.4.

§ 2.1a Diurnal variation of vector direction

Since the direction of disturbing vector of geomagnetic bay changes with local time, it is worthwhile to study how the vector direction of pt's field changes with local time. In view of this point, H. Hatakeyama (1938) has shown the bihourly distribution of direction of disturbing vector of pulsations (Fig. 12). Though he did not distinguish the pt from the whole pulsations, many of his pulsations were probably pt's for use of the quick-run magnetogram in the solar calm years. Recently Y. Kato et al. (1956) showed the similar change of the disturbing vector direction of

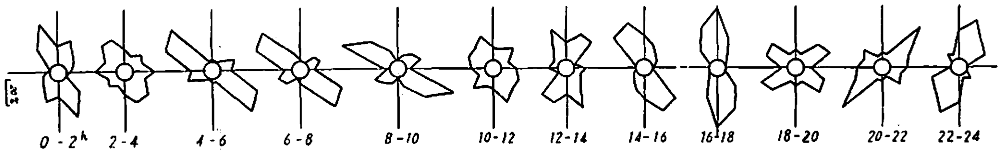


Fig. 12. Bihourly distribution of direction of disturbing vector of geomagnetic pulsation, after H. Hatakeyama, 1938.

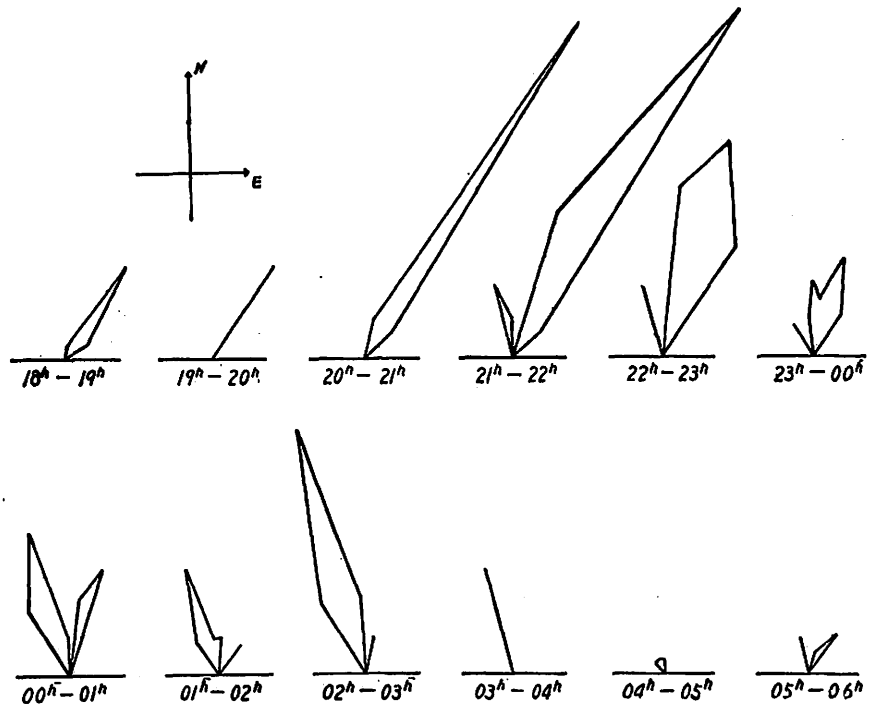


Fig. 13. Direction of disturbing vector of the time derivative field of pt, after Y. Kato and others, 1956.

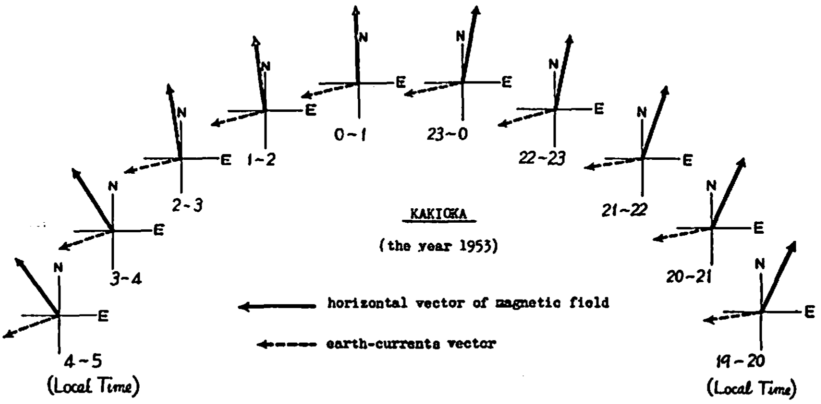


Fig. 14. Change of direction of horizontal disturbing vector of magnetic field of pt deduced from the field of earth-currents.

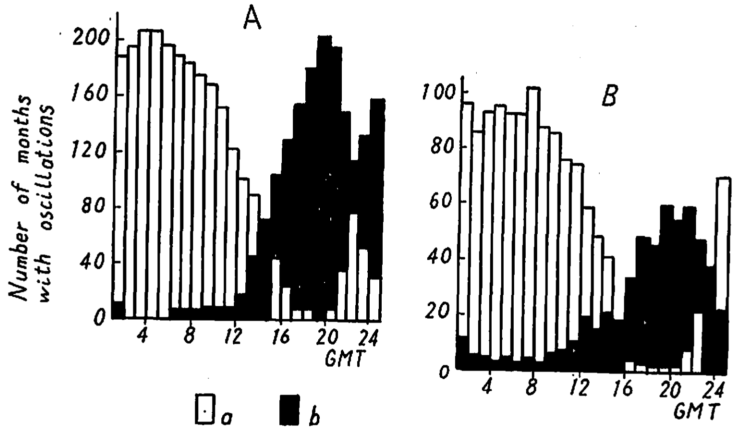
time derivative field which is reproduced here in Fig. 13. Similar result is also given by the present author (Fig. 14).

In these figures the change of direction is restricted mainly in the range of about $\frac{\pi}{2}$, centre of which is NS-direction, in contrast with the full rotation of horizontal disturbing vector of geomagnetic bays. Accordingly, if one tries to show the distribution of the pt-field by an equivalent current system, a possible case firstly considered is a roughly circular current, more of less, along the latitude as it is shown in Fig. 17 in the next section.

§ 2.2 World-wide distribution and GMT control

If one does not miss to select pt, he will find the remarkable local time control in the occurrence frequency of pt such as shown by the curves in Figs. 6-10. From this point of view, one may consider that the occurrence of pt is restricted in night hours only and then the distribution of the field covers only a half of the hemisphere. But the simultaneous occurrences of pt's at several stations far apart each other have been reported by some authors, on the other hand. In the IGY period, the preliminary lists of pt prepared by Dr. Romaña, Chairman of the Committee on Rapid Geomagnetic Variation and Earth-Current, have shown many simultaneous occurrences of pt at the European or African stations and Japanese stations. Therefore, occurrence of pt is substantially a world-wide phenomenon though its amplitude suffers severe local time control.

Some years ago, V. A. Troitskaya (1953) emphasized that there is a remarkable GMT diurnal variation of occurrence frequency of pt for the data from stations widely distributed in USSR. (Fig. 15) The diurnal maximum in occurrence frequency is at about 19-20 h GMT. Our test for detecting GMT control could not find such remarkable GMT curves as Troitskaya's because of the enormous influence of LT control. But the minor change in LT diurnal variation of occurrence frequency with longitudes was found (K. Yanagihara 1957b). The earliest occurrence of maximum at about 19h LT is found at the West-European stations. As one goes to the eastward station from the West-Europe, he will find the more and more late occurrence of the diurnal maximum until he reaches 100°-120° Meridian where the diurnal maximum is found at about 1 h LT. The time of maximum turns there and advances gradually according as one goes again eastwards until he reaches 150°-180° Meridian where the maximum is found probably some hours before the midnight. Thus, the other turning points will be found at about 200°-220° and 270°-300° Meridian. In this process it is noteworthy that in the USSR region, the diurnal maximum is found at earlier hour for the westward station. Thus the local time of the diurnal maximum corresponds to about 19h in GMT for the all stations in the region from Europe to the Central Asia which covers the main area of USSR, provided that the Troitskaya's GMT distribution is considered to represent the LT distribution at Alma Ata. This may be the origin of Troitskaya's result, which is doubtful, in our opinion, for the other regions. Apart from the Troitskaya's enormous GMT control, some GMT variations may exist substantially together with the LT control.



A. Distribution of Type I and Type II oscillations :
  a. Type I oscillations according to earth-current traces at recording-speed 1 mm/sec at Alma Ata and Garm, for December 1951 to August 1952.
  b. Type II oscillatory bursts, according to earth-current recordings in Central Asia for 1951-1952.
B. Distribution of Type I and Type II oscillations for vertical component of the magnetic field, as recorded with months of 1951.

Fig. 15. GMT diurnal variation of occurrence frequency of pt reported by V. A. Troitskaya, 1953.

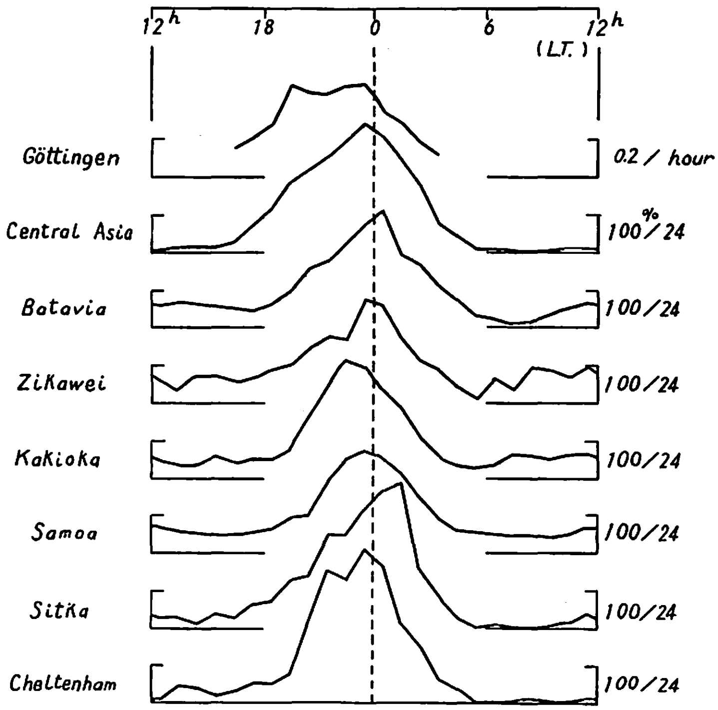


Fig. 16. Change of the LT diurnal variation of occurrence frequency of pt.

The occurrence rate P at an instance is given by the product of those depending upon GMT and LT. (K. Yanagihara 1957b, Y. Kato and T. Watanabe 1959), that is

$$P=P_1(T)\cdot P_2(t),$$

where T and t are the GMT and LT, respectively.

Even in the day hemisphere, pt also occurs in general simultaneously with that in the night hemisphere, but its amplitude is very smaller than that of the later. On the other hand, very few is known about the latitude effect of pt's amplitude. An example has been shown in the Bulletin of IATME, No. 12h, for the simultaneous quick-run records at the six observatories, Lerwick, Lovö, Eskdalmuir, Rudeskov, Witteveen, Chambon-la-Foret and Hermanus. From this data J. G. Scholte and Veldkamp (1955) concluded that the increase of amplitude with latitudes was not rapid so much as bay disturbance.

From the change with latitudes and longitudes and the change in vector direction (§ 2. 1a) the schematic world-wide distribution of pt-field expressed by an equivalent current system is given tentatively (Fig. 17). In the higher latitudes, more large pulsations caused by the other origin may mask the fluctuation due to this currents, and then the observed phenomena are to be discussed in the other way.

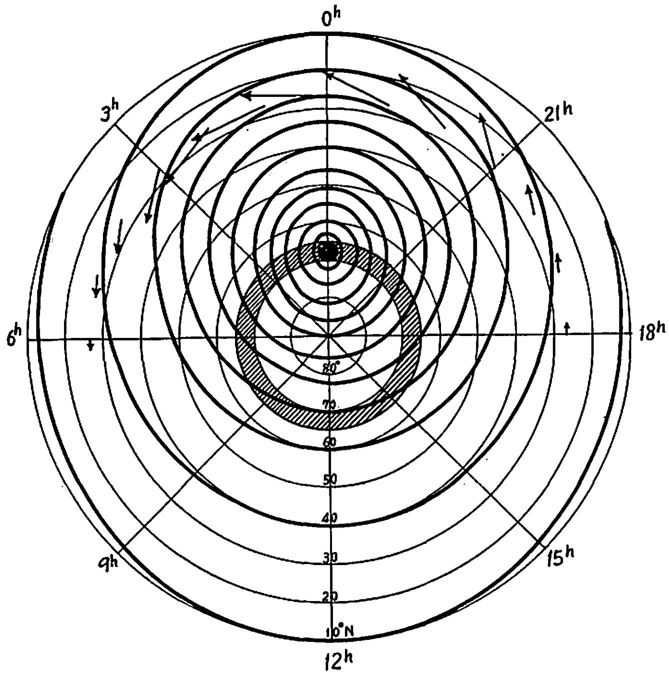


Fig. 17. Suggested schematic distribution of pt-field expressed by the equivalent current system.

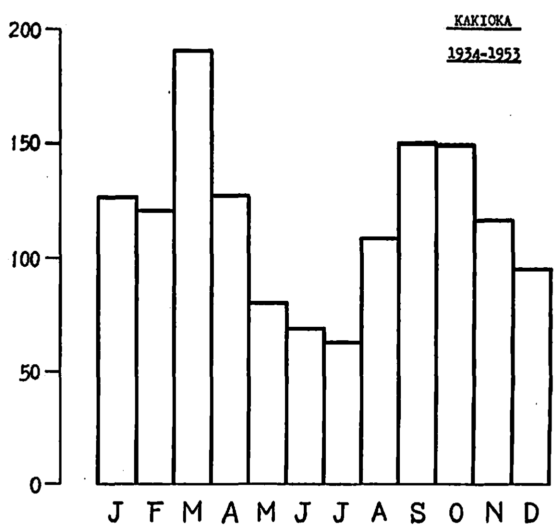


Fig. 18. Mean annual variation of occurrence frequency of pt observed at Kakioka for 20 years, 1934-1953.

§ 2.3 **Annual variation**

The annual variation of occurrence frequency of pt has been reported for 20 year's mean by K. Yanagihara (1957a), and it is reproduced here in Fig. 18. A feature of the figure is the equinoctial maximum, which is generally found in the variation of geomagnetic activity. Rather low level of frequency in summer is also found. To discuss these results it is necessary to take into consideration that the pulsations selected by a severe amplitude criterion were used for the statistical work and then typical and large pt pulsations only have been included.

The annual variation in the sunspot maximum period, such as in the IGY, is different because in that period more small and uncertain pt's may be included to fill the least demand for the amount of data. The annual variation in the year 1958 for pulsations observed at Memambetsu by the induction loop is shown in Fig. 19. Fig. 19(a), in which pt's of all quality A, B and C are included, shows lower frequency in summer months and higher in winter. But the equinoctial maxima are uncertain in the figure. On the other hand, the exquinoctial maxima are distinguishable in Fig. 19 (b) in which pt's of quality A and B only are included.

From the above consideration, it may be concluded that the occurrence of the equinoctial maxima is an essential feature in the annual variation. And occurrence frequency in winter months may be possibly higher than in summer.

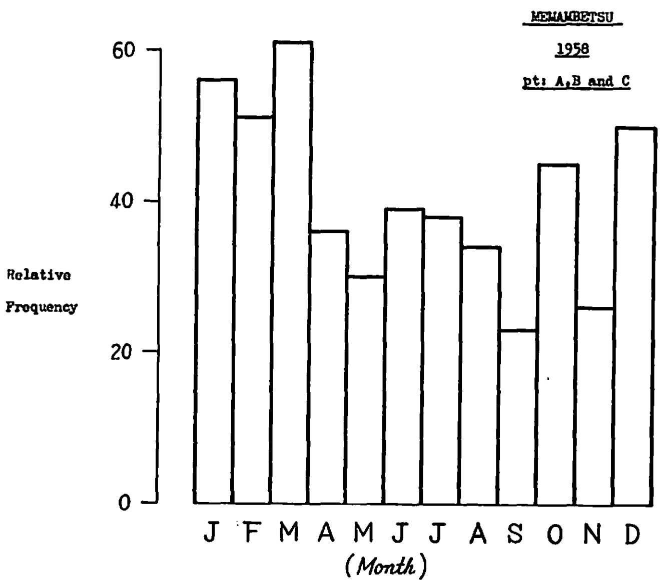


Fig. 19. (a) Annual variation of occurrence frequency of pt observed at Memambetsu with quality A, B and C in the year 1958.

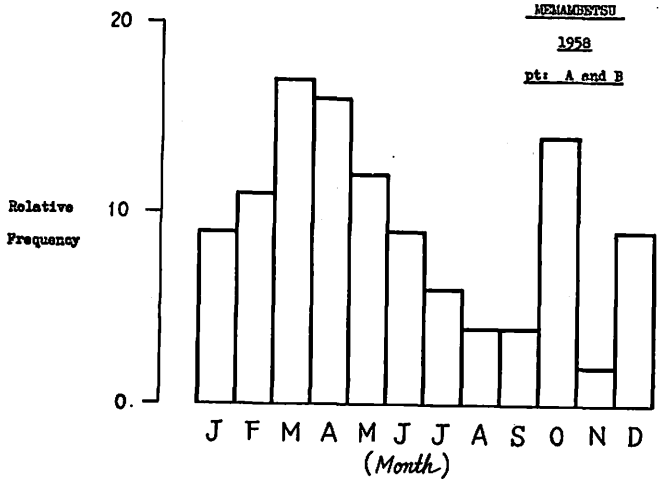


Fig. 19. (b) Annual variation of occurrence frequency of pt observed at Memambetsu with quality A and B in the year 1958.

§ 2.4 11-Year variation

It has been known from old times that pulsations occur not only during disturbed periods but also on otherwise quiet days. But it has remained uncertain till the recent years whether the pulsations are more frequent in disturbed or in quiet years of the 11-year cycle. The author reported (K. Yanagihara, 1956, 1957 a) that

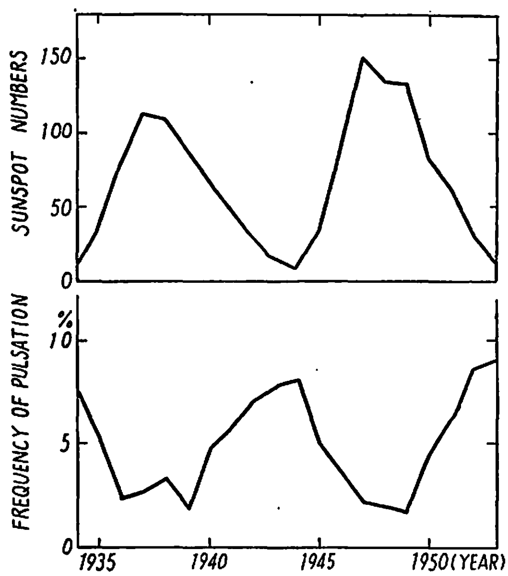


Fig. 20. Year to year variation of occurrence frequency of pt observed at Kakioka.

"night pulsations" occur more frequently in quiet years than in disturbed years, and "day pulsations" show the reverse character. Night and day pulsations are the same as pt and pc, respectively, in the present notation. To study 11-year variation of occurrence frequency, the smallest amplitude of selected pulsations should not be changed during the whole period. And it must be taken into consideration too that if very small pulsations are also counted the variation of occurrence frequency becomes vague because of a saturation phenomenon.

His curve for 11-year variation of occurrence frequency of pt, which is shown in Fig. 20, is obtained by the strict criterion for the above point. The smallest amplitude of his pulsation pt's in the curve is 20 mv/km in the earth-currents at Kakioka, which is about the same as the range of diurnal variation. By this criterion, it is deduced that the all selected pt's are large and typical. The number of selected pulsations exceeds a hundred or more in the calm years of the 11-year cycle, though only a few are found in the sunspot maximum years.

The 11-year variation of occurrence frequency of pt shows clearly the inverse proportionality to the sunspot numbers in yearly mean. Some crests of the curve in the sunspot maximum years seem to be due to the activity of disturbance-type pt (K. Yanagihara 1957 a) which is accompanied with storms and may have rather

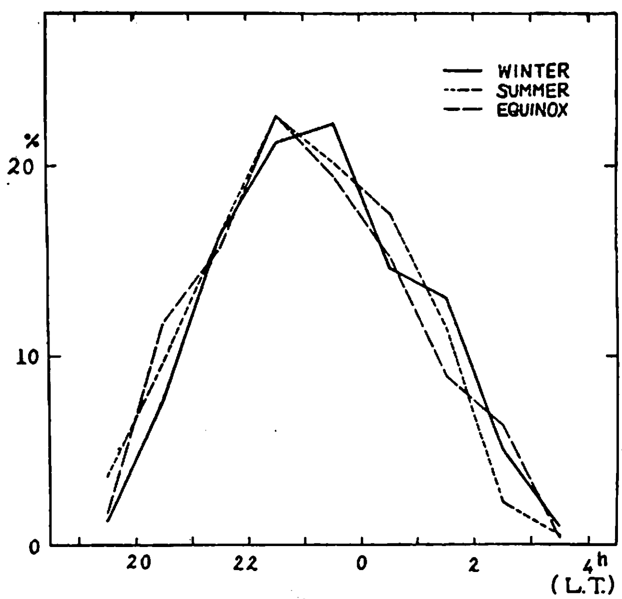


Fig. 21. Normalized diurnal variation of occurrence frequency of pt observed at Kakioka for each season.

normal feature of activity varying parallel with the solar activity during the 11-year cycle. (c.f. § 5.1)

If the ionospheric conductivity controls considerably the observed occurrence frequency of pt through a manner of screening effect or so, inverse proportionality of occurrence frequency to the sunspot number in yearly mean is easily explained. But many negative evidences appeared to be found. For example :

(i) It is not possible to understand the reason why the ionospheric screening acts effectively upon pt only and does not on pc which has the positive dependency on the solar activity in yearly mean.

(ii) The normalized diurnal variation of occurrence frequency does not depend upon season regardless of the different diurnal variation of the ionospheric conductivity in each season (Fig. 21).

(iii) A theoretical calculation following Ashour and Price's (1948) assumption shows that the calculated amplitude along the midnight meridian decreases from the maximum on the equater to the minimum near the auroral zone. This tendency is not the same as the observed one. (Fig. 22).

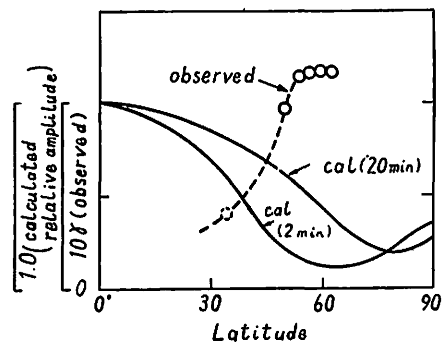


Fig. 22. Calculated and observed latitudinal changes of amplitude of pt.

Thus the ionospheric screening effect is not considered to be a probable cause for the inverse proportionality of occurrence frequency to the solar activity in yearly mean. From the hydromagnetic point of view, the change of the acivity to obstruct the travel of hydromagnetic waves in the outer atmosphere is a probable cause for the 11-year variation as well as for the diurnal variation of occurrence frequecy. This view will be discussed in § 5.4.

Chapter 3 Characters of pt in Relation to Geomagnetic Disturbance and Classification of Pulsations

§ 3.1 Relation between pt and geomagnetic activity

Apart from the fact that the occurrence frequency of pt in yearly mean is inversely proportional to the relative sunspot numbers, more opportunity for occurrence of pt is afforded at the time of higher geomagnetic activity. Fig. 23 shows the occurrence rates of pt for each geomagnetic activity level in Kp-index. The curves of Fig. 23(a) is given from the data of large and typical pt observed by the earth-currents at Kakioka during 17 years, 1937–1953. On the other hand, Fig. 23 (b)

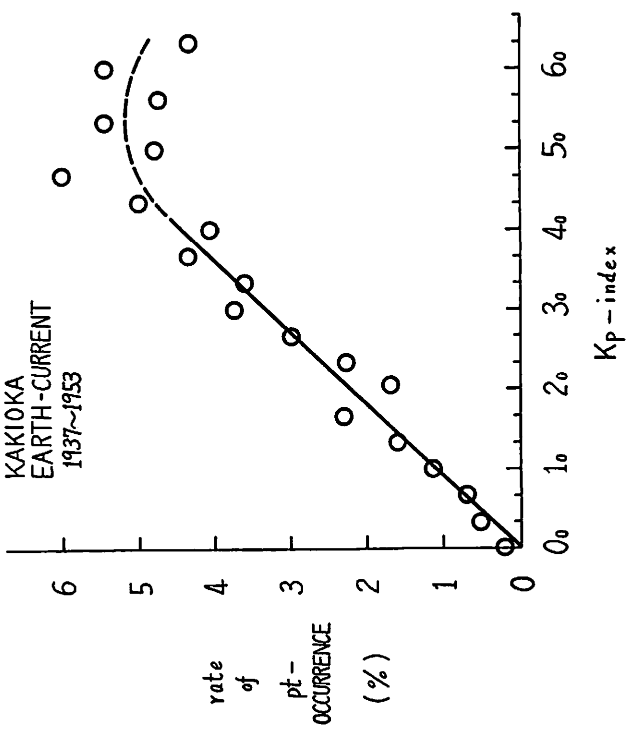


Fig. 23. (a) Change of the rate of occurrence of pt with Kp for large and typical pt during 17 years.

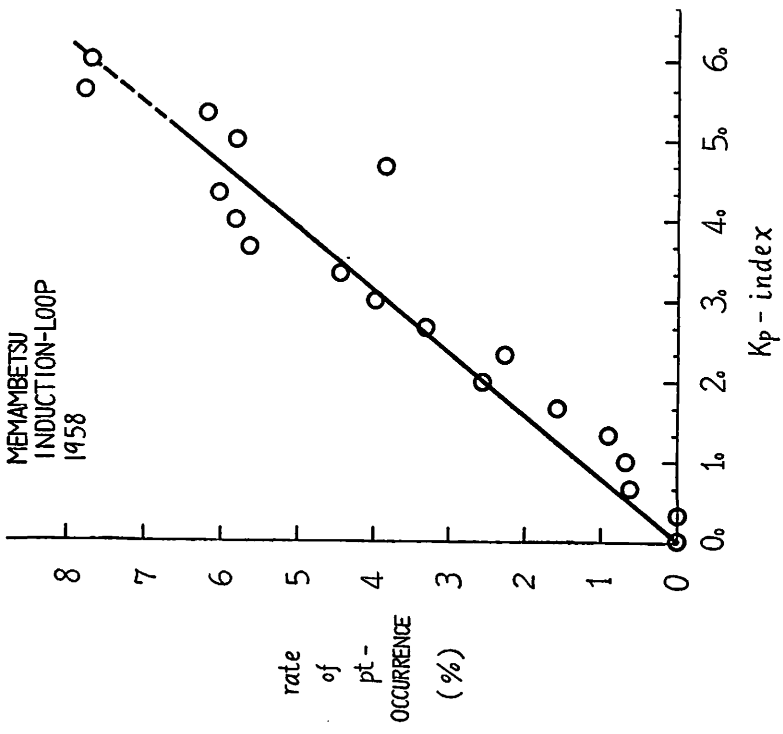


Fig. 23. (b) Change of the rate of occurrence of pt with Kp for whole pt having the quality A, B and C in the year 1958.

shows the curve obtained from the data including rather small pt observed at Memambetsu by induction magnetograph during the one year 1958, when the solar activity is maximum and the pt activity is minimum. Both curves show the linear relation between occurrence rate of pt and Kp-index for the range of Kp from 0 to about 5. For the higher geomagnetic activity levels, Kp>5, the relation is not clear because of the few data. At the time of these high activity levels when geomagnetic storm develops generally, it is difficult to distinguish pt from irregular overlapping fluctuations. And moreover, wave forms of pt's become complex and irregular, some modifications for the definition of pt being necessary to study storm time pulsations, which will be disucussed in later sections.

The diurnal variation of occurrence frequency of pt pulsations is affected by the geomagnetic activity level. Fig. 24 shows three curves of hourly occurrence frequency for $Kp=0_0-2_+$, 3_--4_+ and 5_--6_+, respectively. It is remarkable that the curve for $Kp=0_0-2_+$ is well symmetrical about the maximum at about 23.5 h LT. As the geomagnetic activity level becomes high, the maximum of hourly frequency of pt occurrence is found at the earlier hour. For $Kp=5_--6_+$, the maximum of frequency is found at about 22 h LT, and second maximum occurs after midnight. This tendency is the same as that found in the diurnal variation observed in the sunspot maximum years such as in Fig. 8. Since the mean level of geomagnetic activity in the sunspot maximum years is higher than in the minimum years, the above agreement is reasonable.

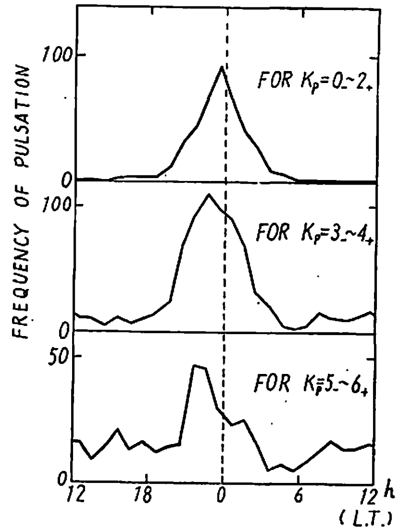


Fig. 24. LT diurnal variation of occurrence frequency of pt for each Kp-level.

§ 3.2 World-wide pattern of geomagnetic activity

Since the occurrence of pt pulsation statistically depends upon the geomagnetic activity, to explain the variation of occurrence frequency of pt some features of time and space inequality of geomagnetic activities should be studied. An explanation of the GMT control on the occurrence frequency of pt was tested by the present author (1957b) using the GMT diurnal variation of geomagnetic activity which was reported by S. B. Nicholson and O. R. Wulf (1955). Their GMT diurnal variation of K-index was calculated neglecting the latitudinal change.

On the other hand, the spiral pattern of the world-wide distribution of geomagnetic activity was reported by some authors J. H. Meek, 1955, E. R. Hope 1956, and A. P. Nikolski, 1956 and 1957. Meek re-examined the Polar-Year data of E. H. Vestine (1947) and found a spiral pattern in the polar plot of the local geomagnetic time of the diurnal maximum decrease or increase in H of SD. But, as to the features in the higher latitude than 65°, another conclusion may be deduced from the same data of Vestine. Disturbance daily variation of H at the station ranged from 65° to 75° in geomagnetic latitudes shows two minima in general. The curves of Point Barrow (68.6°), Fort Rae (69.0°), Julianne Haab (70.8°), and Chesterfield Inlet (73.5°) shown in the Vestine's Fig. 91 (A) are the case. If the time of the second decrease (cross) as well as the time of lowest decrease (circle) is plotted, Meek's exceptional case is smoothly connected with the others. (Fig. 25) But the curve branchs off at

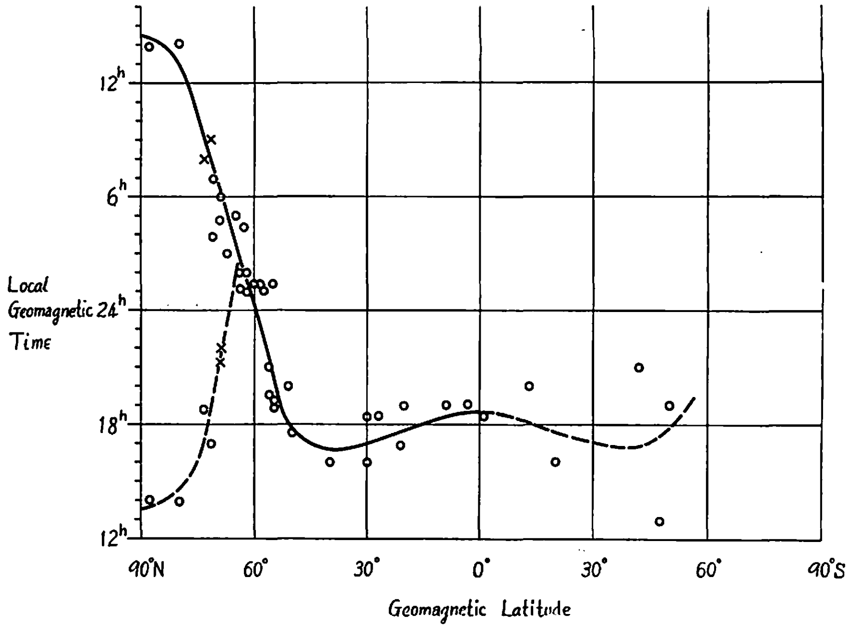


Fig. 25. Local geomagnetic time of the minimum of disturbance daily variation of H for various latitudes.

about 65° and then the spiral pattern is modified.

It is doubtful that the spiral of the diurnal maximum decrease in H is immediately connected to the precipitation spiral of the solar particles. From the Chapman's idealized SD current sysem which is symmetrical about axis it is found that the time of maximum decrease in H is 18 h in the polar cap, 6 h in the auroral zone and 18 h in the middle or low latitude. Smoothly connecting these times of maximum decrease in H, the spiral-like pattern can be shown and the branched curve is also explained. Then, it may not be said that the spiral pattern of the diurnal maximum decrease in H is mainly due to the precipitation spiral of the solar particles, though Vestine's SD current system differs from the idealized one and some possibility of spiral-like pattern which is not apparent is still remained.

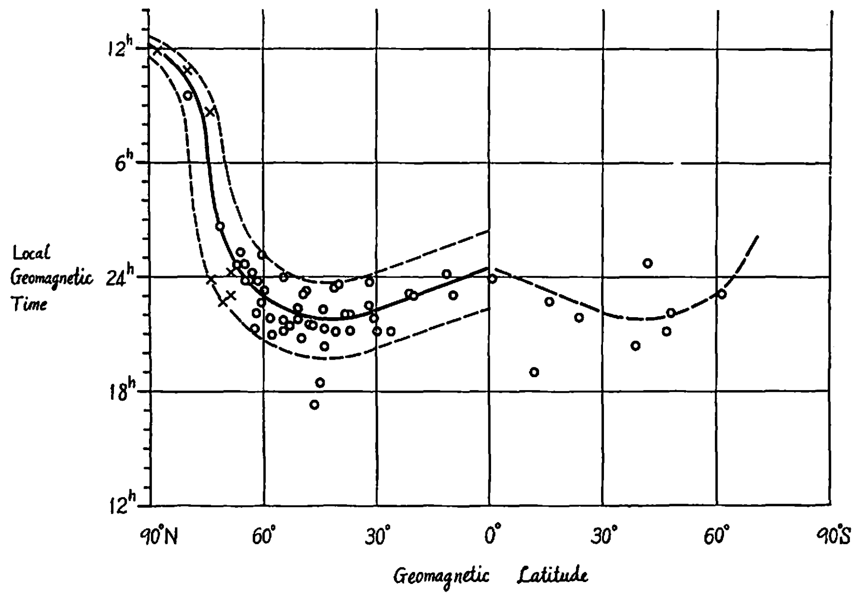


Fig. 26. (a) Local geomagnetic time of diurnal maximum of K-index for various latitudes.

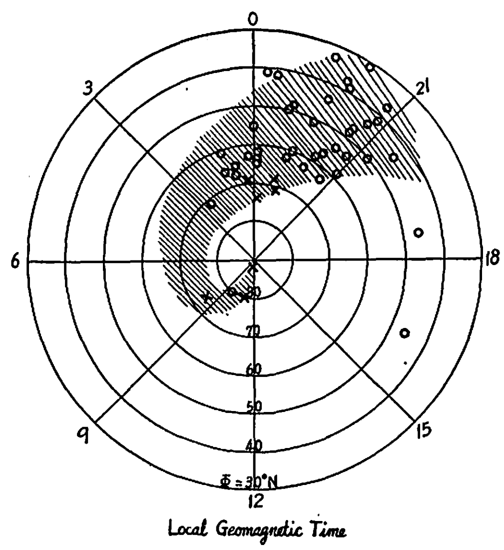


Fig. 26. (b) Polar plot of the local geomagnetic time of diurnal maximum of K-index.

Recently T. Obayashi (1959) studied the world-wide pattern of the abnormal increase of f_{min} associated with the severe magnetic storm and found the spiral-like pattern. Since the abnormal increase of f_{min} associated with magnetic storm is considered to be caused by the invasion of solar particles, its spiral-like pattern informs more directly the feature of precipitation spiral.

Using the diurnal variation of K-index the world-wide pattern of geomagnetic disturbance will be re-examined in the following. K-index may be a better measure of geomagnetic disturbances than one component only of the field such as H, though it is not an ideal measure. The local geomagnetic times of diurnal maximum of K-index are shown in Fig. 26 for many stations from 88° geomagnetic north to 61° geomagnetic south. The points shown by circle in the figure are due to the data of the equinoctial month of the year 1955. The rest expressed by cross is due to the Second Polar Year data which is added because of the lack of high latitude data in the Bulletin of IATME No. 12 i for 1955. The spiral pattern is also found in the figure for the time of the diurnal maximum of K-index, but somewhat differs from the Meek's apparent spiral.

In addition to the general latitudinal change, a longitudinal inequality of the time of the diurnal maximum of K-index is also found. The deviation in hour of the observed time of diurnal maximum of K-index from the mean time deduced from the mean latitudinal change is plotted for the abscissa of longitude (Fig. 27). The observed local geomagnetic time of diurnal maximum advances or retrogresses from the mean time according to the longitude of the observing station irrespective of its latitude. These advances or retrogressions repeat twice in the whole circle 360°. The most retrogressions occur at about the meridian containing the geomagnetic dipole axis. Since the mean curve of the latitudinal change in Fig. 26 intersects

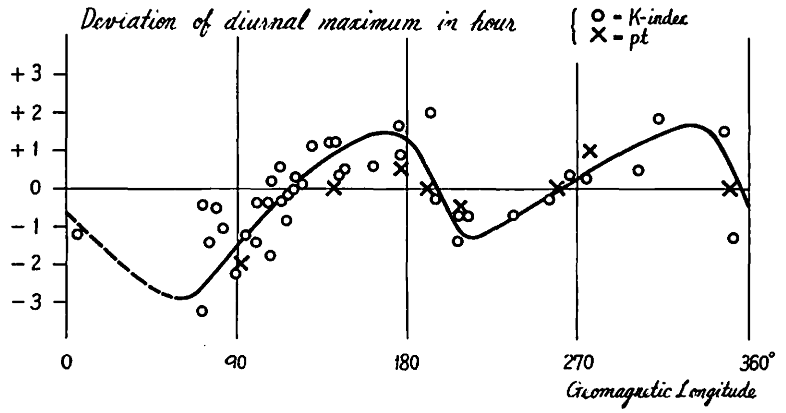


Fig. 27. Deviation in hour of the observed time of diurnal maximum of K-index from its mean for various longitudes.

the 24 hr-line at the auroral zone latitude, in this latitude zone the highest disturbance activity occurs about two hours late from midnight in the meridian containing geomgnetic axis pole, and does about two hours before midnight in the meridian which is 90° distant from the former one. These features mean a GMT control of the inclined geomagnetic axis on the presipitation of the solar particles.

A test for explaining the GMT control on the occurrence frequency of pt pulsations using the Nicholson and Wulf's GMT diurnal variation of K-index was made already by the author (1957 b). But their GMT diurnal variation of K-index was calculated from the data in the middle or low latitude neglecting the latitudinal change. And then it is doubtful that this GMT variation make a measure of the GMT control on the invasion of solar paticles which occurs mainly in the higher latitude. Using the now obtained GMT control shown in Fig. 27, in place of the Nicholson and Wulf's GMT diurnal variation of K-index, the longitudinal inequality of the time of maximum frequency of pt-occurrence shown in Fig. 16 is reasonably explained.

Deviations of the time of maximum frequency of pt-occurrence from the mean is plotted in Fig. 27 by cross, these points being well in accord with the general tendency of the other points of K-index. Thus, the GMT control on occurrence of pt seems to be substantially the same phenomenon as that of geomagnetic activity. The invasion of the solar particles may produce disturbance currents in the ionosphere which are the main cause of DS or DS-like disturbances, increasing the value of K-index and fluctuation fields in the outer atmosphere which is the cause of pulsations. In the case of pulsations, the latitudinal change of the time of diurnal maximum may be not so effective, differing from DS or DS-like disturbances which are severely controlled by the ionospheric conditions.

§ 3.3 Occurrence of pt during geomagnetic storm and existence of irregular but pt-like pulsations

It is often said in the previous sections that occurrence of pt is closely connected to geomagnetic disturbances especially to polar storms or geomagnetic bays. But its occurrence during storm remains unstudied because of the irregularity of fluctuation. Judge of the class of pulsations is very difficult in that period. The present classification is not sufficient for pulsations in the period of heavy disturbances (K. Yanagihara 1957 (a)).

Frequency of occurrence of pt selected by the present criteria is very high during some storms, but it is nearly zero during some other storms. And then the statistically deduced relation between storm and pt-occurrence is very weak. Out of the 26 days in the year 1958 having ΣK larger than 30, 5 days have active occurrences of pt at Memambetsu. In the rest 21 days, pt is hardly found. Studying in detail

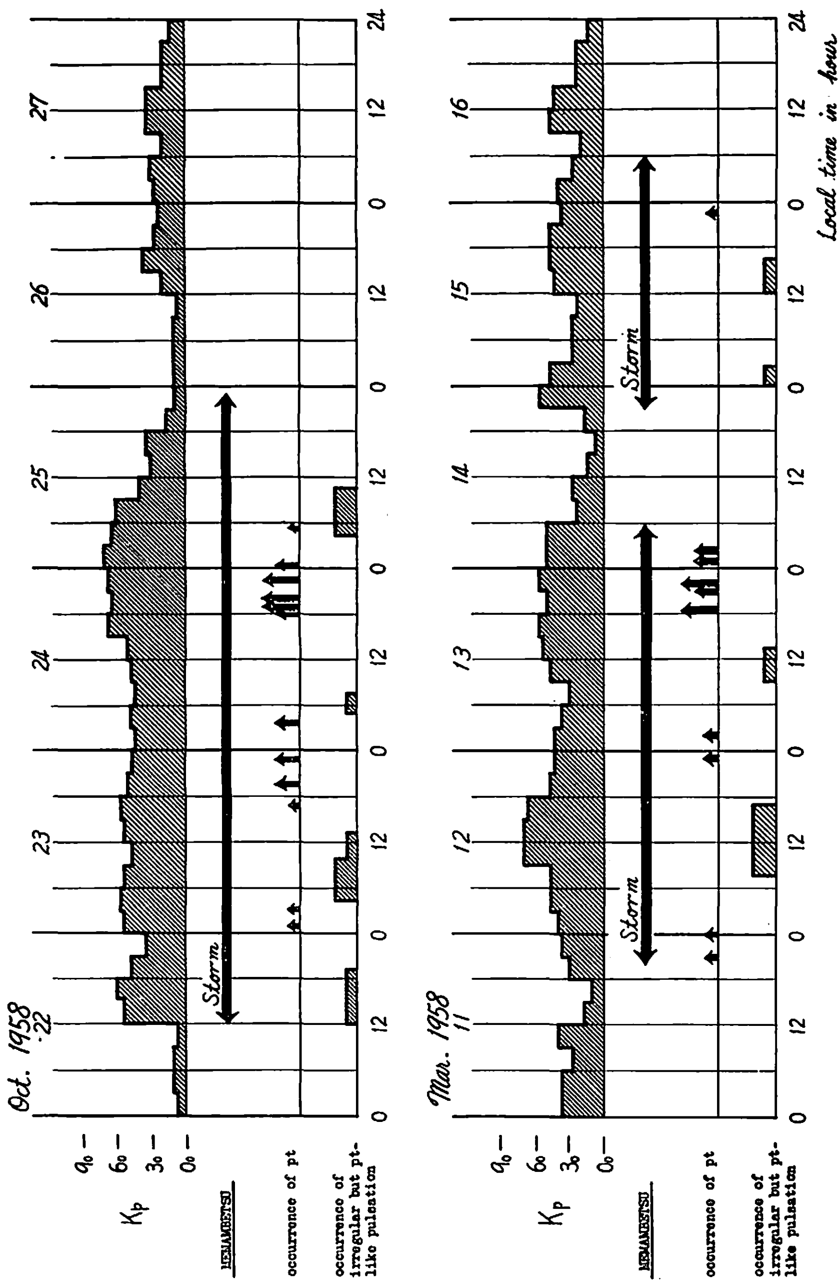


Fig. 28. Occurrence of irregular but pt-like pulsations and high geomagnetic activity or storm.

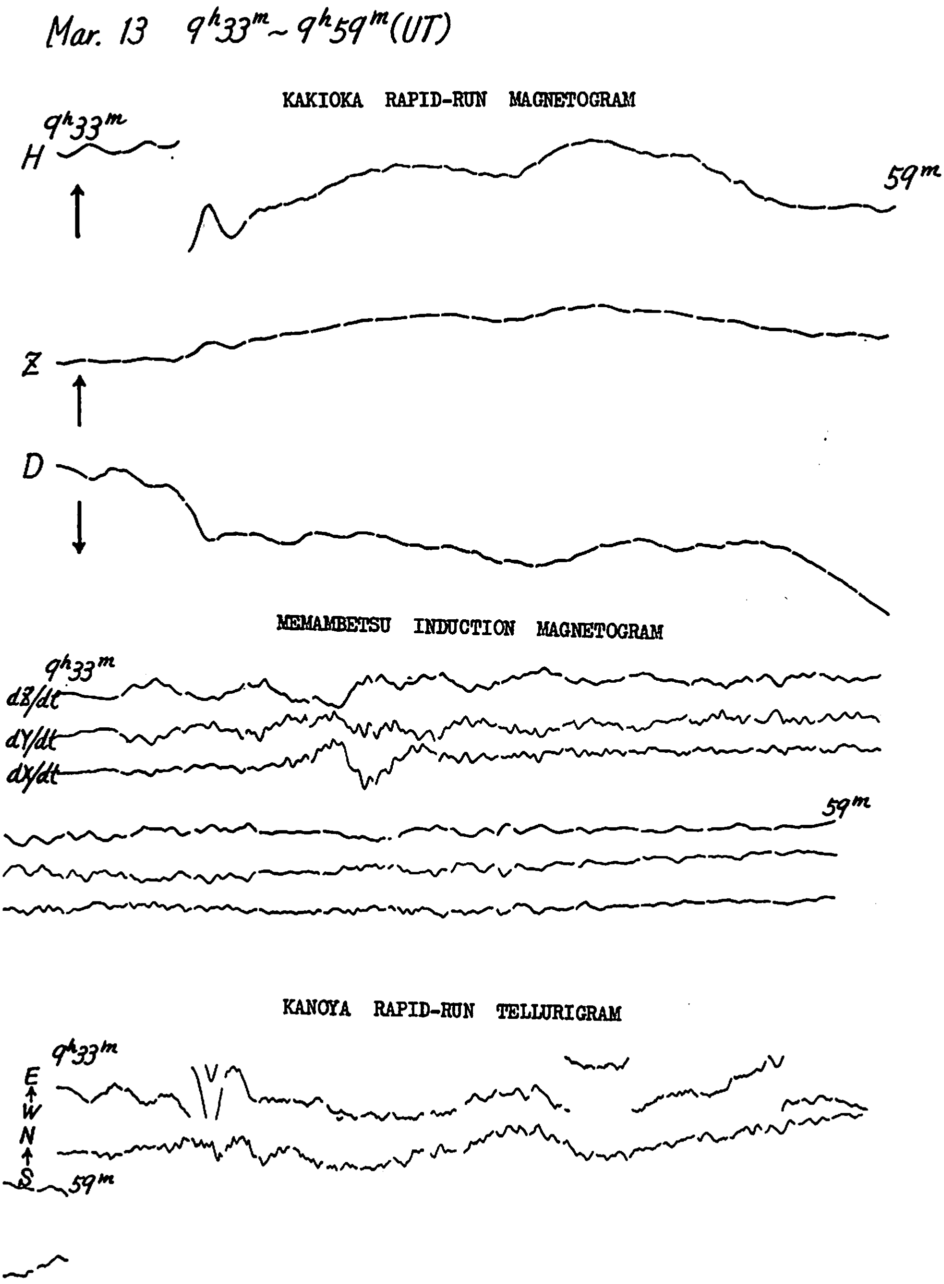


Fig. 29. (a) Examples of disturbance-type pt.

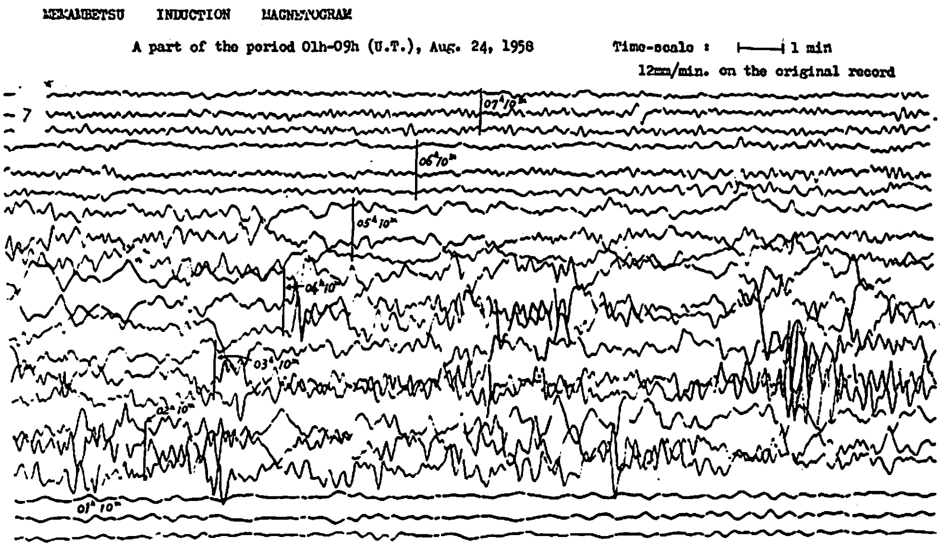


Fig. 29. (b) Example of irregular but pt-like pulsation.

the cases that pt occurs actively in the days having large Σ Kp, it is deduced that the occurrence of pt in the storm time is found at Memambetsu only when Kp is larger than about 5 in the night hours of the station (Fig. 28). In contrast with this, pt is not found during the storms which have no large Kp in the night hours of the station.

The pt in storm period is somewhat different from the typical pt in calm period. Duration of its individual series is rather long, and overlapping oscillations which have shorter period of 5-20 sec are more active than fundamental oscillation of pt. This class of pt will be called disturbance-type or d-type pt in the following of this paper. As the irregular feature of d-type pt develops, it becomes inadequate to class into "pt". This case is found in irregular but pt-like pulsation at the day hemisphere during storms, or at the night side during severe storms which have very large Kp of 7-9. Such irregular fluctuation has still pulsative or oscillative character, its period being about the same as that of fundamental oscillation of pt. But the separation of individual series is very vague and the whole phenomena often continue intermittently for some hours or more. If the irregular but pt-like pulsation is taken into consideration, all storms have active occurrence of pt or pt-like pulsations during the period of which Kp-value is larger than about 5 (Figs. 28, 30).

§ 3.4 T-index for pt and pt-like pulsations and its application to analysis of geomagnetic storm

Since pt pulsation occurs rather isolatedly, its activity is given to some extent by frequency of occurrence. For the study of activity of pt and pt-like pulsation during storm, however, it is not sufficient to know only the frequency of occurrence, because a sequential expression of activity is needed and the frequency of occurrence has no meaning for long continual irregular pt-like pulsation. Then a test to prepare indices for measure of activity is examined.

It is considered to be reasonable that the normal duration of series of pt, 10 minutes, is given for unit period of the index. An index of pt and pt-like pulsation in each 10 minutes is decided in the scale 0 to 3 by the two criteria for amplitude and type of oscillation. This indices are called hereafter "T-indices". T-index 0 is given when pt or pt-like pulsation is little active or not found in the period. T-indices 1, 2 and 3 are given by the criteria shown in table 2, where 3 classes, A, B and C, of amplitude and types corresponding to distinct, fair and ordinary, and small or somewhat doubtful groups, respectively. For example, ranges of 3 classes, A, B and C, of amplitude for the induction magnetogram at Memambetsu are given as follows :

class A	mean amplitude $> 0.4\gamma$/sec
class B	$0.4 \geqq$ mean amplitude $> 0.2\gamma$/sec
class C	$0.2 \geqq$ mean amplitude $> 0.04\gamma$/sec

Table 2. Criteria for T-indices 1, 2, and 3

Type \ Amplitude	A	B	C
A	3	3	2
B	3	2	1
C	2	1	1

An hourly index Th is a sum of six T-indices which are given for the period 0-10 min, 10-20 min, 20-30 min, 30-40 min, 40-50 min and 50-60 min of the hour concerned. It is suitable for usual analysis of disturbances to use the hourly index Th. An example of Th-indices in a month is shown in Fig. 30 together with Kp-indices. High correlation between Th-indices and Kp-indices is recognized in the figure or Fig. 31.

T-indices have been scaled for 36 storms in the period of the IGY. The mean storm time variation of Th-index for 30 sc-storms and 6 non-sc-storms are shown in Fig. 32. The mean local time variations are given in Fig. 33 for the first, second and preceding days of the storms.

Th-index rises suddenly at the time of the onset of sc-storm, and gradually decreases as it is expected. The highest level of Th-index is found in the first several hours which correspond to the initial phase of storm. And then the activity decreases in the whole period of the main phase. This fact is an interesting fact,

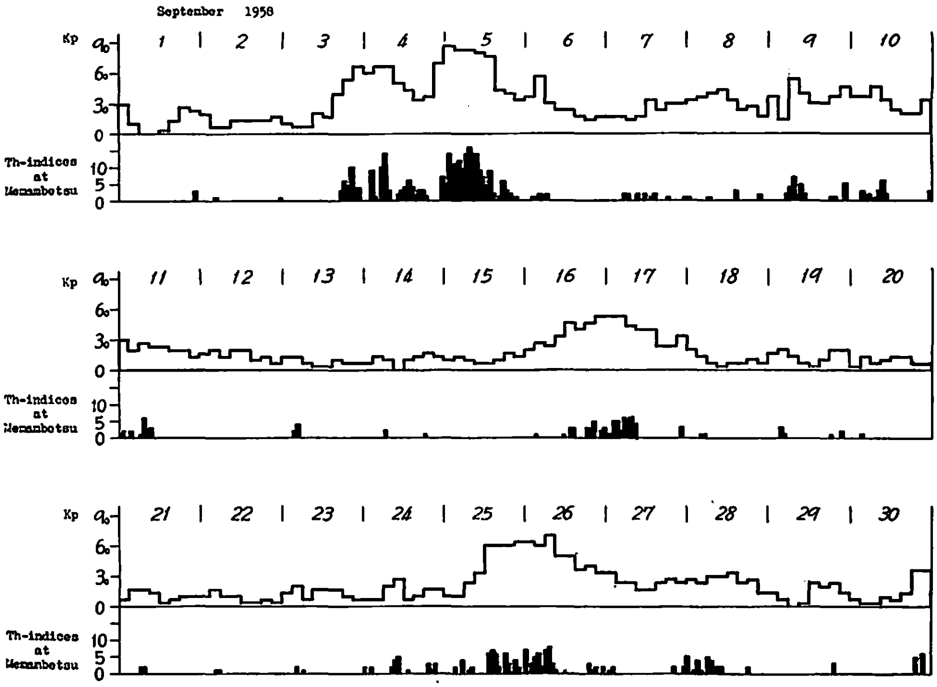


Fig. 30. Th- and Kp-indices during September, 1958 at Memambetsu.

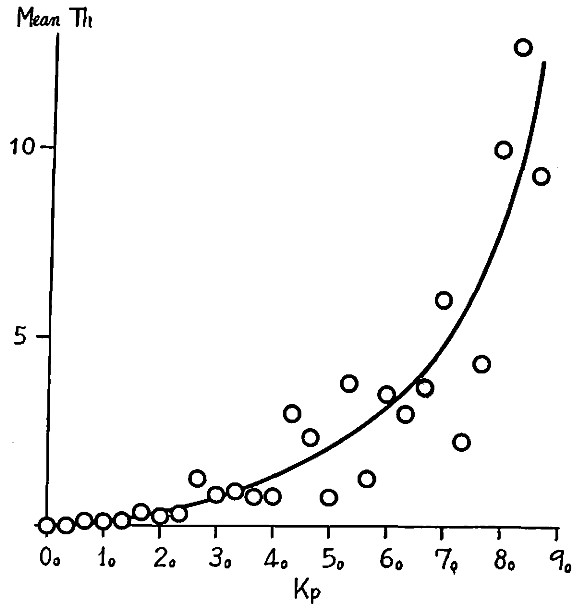


Fig. 31. Correlation between Th- and Kp-indices.

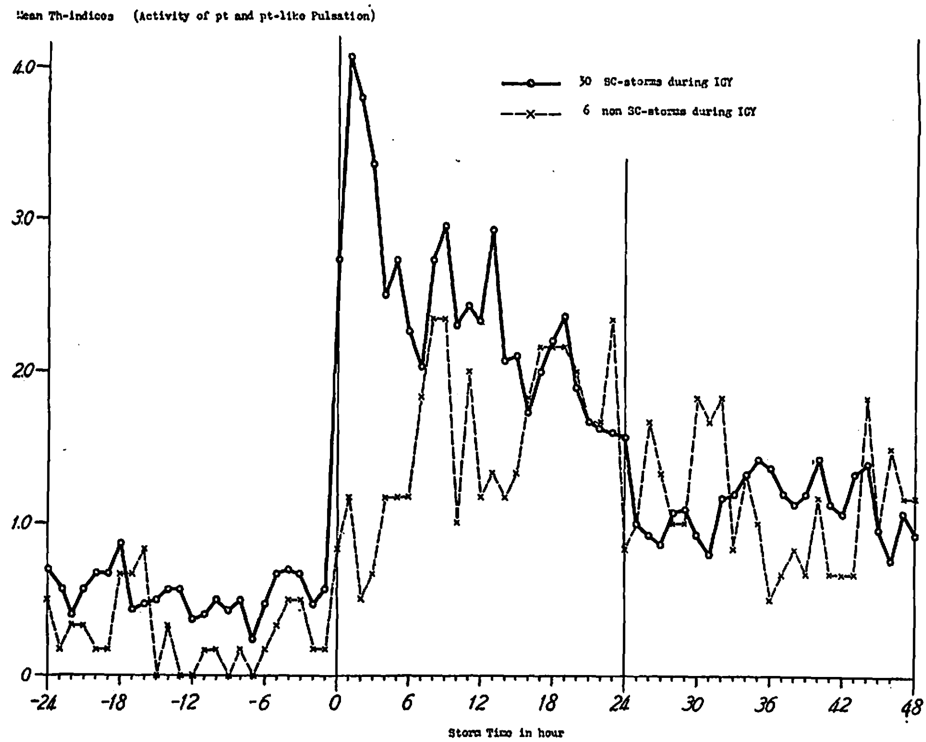


Fig. 32. Storm time variation of Th-index for 30 SC-storms and 6 non-SC-storms during the IGY

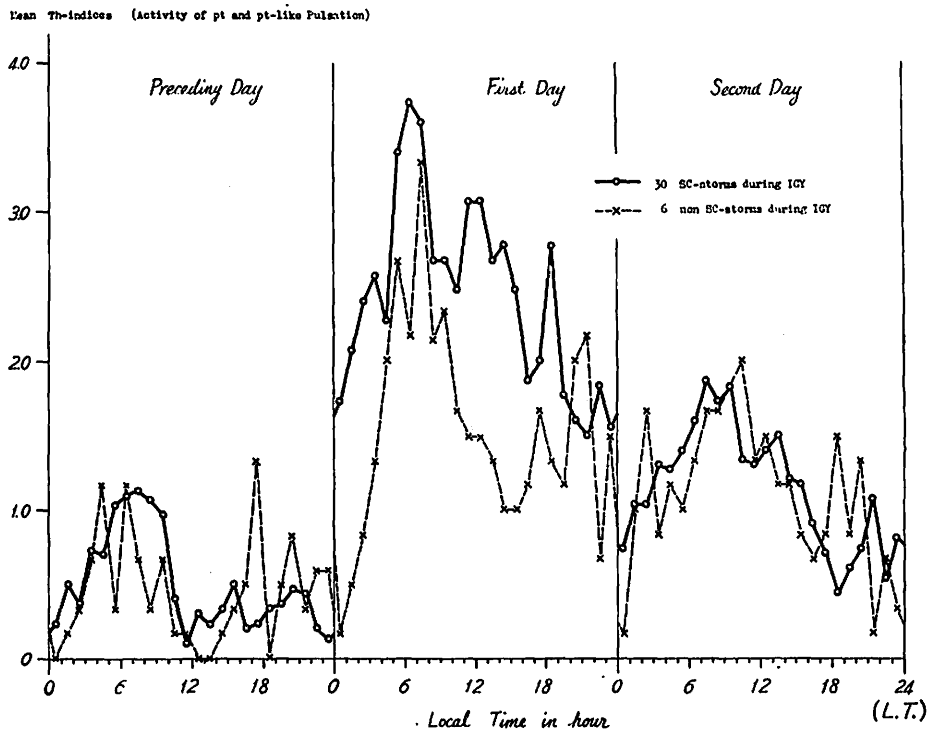


Fig. 33. Local time diurnal variation of Th-index for the storm period during the IGY.

because the invasion of the solar particles may be more active in the initial phase than in the main phase if pt or pt-like pulsation accompanies the invasions of solar particles. On the other hand, the storm time variation of Th-index for non-sc-storms shows uncertain features of gradual increase and later occurred maximum.

The diurnal maximum of Th-index during storms occurs at about 7h in local time, but it is uncertain whether the maxima occur everywhere at the same hours in local time or universal time. Using the latitudinal and longitudinal change of K-index obtained in § 3. 2, it is deduced that the diurnal maximum of K-index occurs roughly at about 22 hour in GMT in the first quarter (0°-90°) of the auroral zone and at about 10 hour in the third quarter, 180°-270°. In the other two quarters of the auroral zone, the occurrence time of the diurnal maximum in GMT changes rapidly according to the longitude, as it is expected from the GMT control shown Fig. 27. Invasion of solar particles can be therefore active at 22 h or 10 h in GMT. It is very probable that the diurnal maximum of Th-index at 7 h in local time at Memambetsu which corresponds to 22 h GMT may arise from the same reason.

§ 3. 5 Very short period oscillation spt accompanying pt

The induction magnetographs used at Memambetsu and Kanoya during the IGY have the improved frequency responses which are shown in Fig. 5, the paper speed being 12 mm/min. Then an oscillation having the period of about 5 sec or so can be clearly distinguished. As the result, some behaviours of short period oscillations

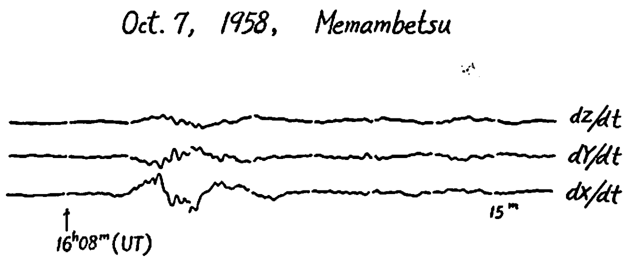


Fig. 34. Example of spt.

have been clearly shown. One of the behaviours is the occurrence of short period oscillations accompanying pt, which have been called spt by the author (K. Yanagihara, 1959).

Observed characters of spt are outlined as follows.

(i) In the 202 pt's selected from the induction magnetograms in the year 1958 at Memambetsu, 179 cases are accompanied with spt.

(ii) The beginning of spt almost coincides with that of pt. In the case that a continuous oscillation with period of 5-10 sec is existing before the beginning of pt, the oscillation becomes more active after the onset of pt.

(iii) The period of most spt's ranges between 5 sec and 10 sec. As to the oscillation having the shorter period than 5 sec, it is difficult to draw a definite result with respect to its occurrence because of the low sensitivity of the measuring apparatus for such frequency. On the other hand, occurrence of the oscillation having longer period than 10 sec is found at the time of occurrence of d-type pt. When an irregular but pt-like pulsation occurs accompanying storm a pulsation of pc probably takes the place of spt.

(iv) The period of spt does not depend upon the period of the main oscillation of pt (Fig. 35).

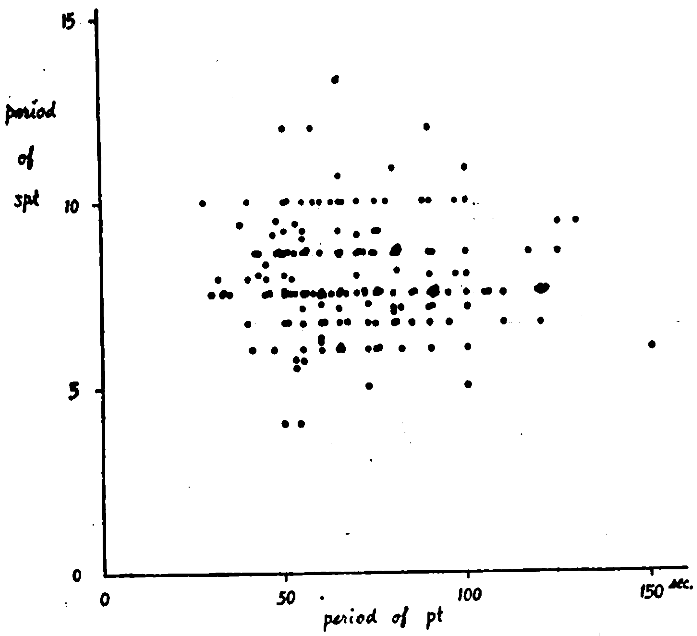


Fig. 35. Period of pt and spt.

(v) When spt's are observed at Memambetsu (43° 55′ N, 144° 12′ E), the induction magnetograms at Kanoya (31°25′ N, 130°53′ E) show the same spt's. Then, spt's are not artificial phenomena.

(vi) In the solar calm years, spt's are also found. But they are less active in the period, though pt's occur most frequently.

(vii) The continuous pulsation pc which has the period between 10–40 sec predominates in the daytime. In the night hours, on the other hand, a continuous pulsation having the shorter period between 5–10 sec occurs frequently. This continuous pulsation has similar characters to spt, especially for its period.

§ 3.6 Classification of pulsations

It has been shown that pulsations observed in middle or low latitude can be roughly classified into two groups, pt and pc. And some necessary modifications or additions for the classification of pulsations have been discussed sometimes in the preceding sections. To make a further study ot pulsations, re-examination of the classification is necessary in the present status.

An occurrence of the typical pt is found at the time of bay disturbance. As the general level of the geomgnetic activity becomes high, occurrence of "typical" pt decreases. During storms, pt's, typical or not, scarcely occur, but the modified pt's which are the irregular but pt-like pulsations in § 3.3 are found frequently in general.

Taking into consideration the behaviour of pulsations during storms, pt and pt-like pulsation can be divided into the following three classes.

(i) calm-type pt (c-type pt)

(ii) disturbance-type pt (d-type pt)

(iii) irregular but pt-like pulsation

The pulsation of the first or second class is the "pt" itself described in the Copenhagen Resolution. The last class pulsation may not be the same as the "pt" because they lose the essential character for pt that is the assembly of series lasting for limited duration. Examples of each class pulsations are shown in Fig. 1(a) and Fig. 29 (a) and (b). Their characters are described as follows :

(i) calm-type pt : This is the typical pt and its description was given as follows at the Copenhagen Meeting of the Committee on Rapid Magnetic Variation and Earth Currents.

pt : A phenomenon consisting of several series of oscillations, each series lasting generally 10 to 20 minutes, the whole phenomenon lasting for periods of not more than about one hour.

Besides this description, the following characters are remarkable.

(a) The fundamental period of oscillation is somewhat longer than that of pc. Examples of period spectrum are shown in Fig. 36 (a) and (b). They are the period spectrum for the solar calm years given by Y. Kato et al. (1956) and that for the sunspot maximum years by the present author. Most frequently occurring periods are different for the respective years. They are about 40 sec and 70 sec.

(b) Each oscillation has not the regular sinusoidal form but has rather pulsative one. It's peculiar form is shown exaggeratively in the upper part of Fig. 3. It is noteworthy that this form possesses the second minimum together with the main minimum. Since the form of oscillation in the sunspot minimum years has the remarkable second minimum, its period is apt to be estimated to the half of the case that the second minimum is not clear (the lower part of Fig. 3). This may be the

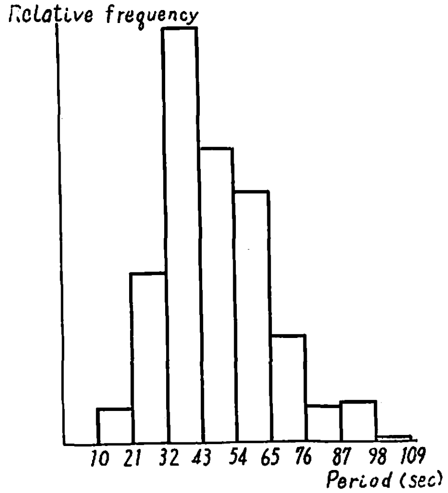


Fig. 36. (a) Period spectrum of pt observed in the sunspot minimum years after Y. Kato et al, 1956.

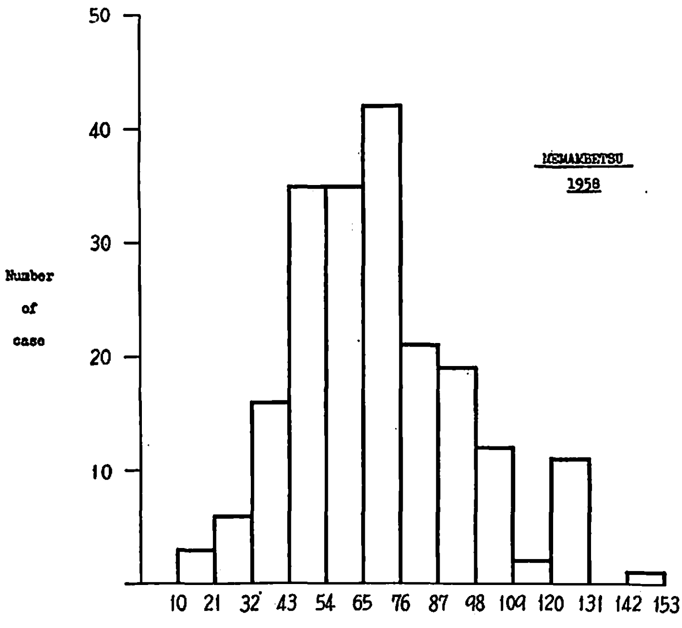


Fig. 36. (b) Period spectrum of pt observed in the sunspot maximum year, 1958, at Memambetsu.

cause for the difference between the most frequently occurring periods of pt in the sunspot maximum years and that in the minimum years described in the preceding item.

(c) Very short period oscillation, spt, overlaps almost always. Its period is usually shorter than 10 sec, but its relative amplitude is rather small even on the well sensitive induction magnetogram.

(ii) disturbance-type pt : This type occurs generally in the night hemisphere during storms. Each series of oscillations last often for half an hour or more, that is longer than the duration of series of calm-type pt. The period of overlapping oscillation, spt, is usually longer than 10 seconds and its recorded amplitude exceeds sometimes that of the main oscillation of pt on the induction magnetogram. Therefore, on the record the fundamental oscillations having the period of several ten seconds are obscured and the more short period oscillations, spt's, are distinct. The whole phenomenon of disturbance-type pt have often only one series having comparatively long duration, such as one hour.

(iii) irregular but pt-like pulsations :

The case that the irregular features of disturbance-type pt are developed is the subject of this item. An irregular but pt-like pulsations usually occur in the day hemisphere during storms. The whole phenomenon often continues for many hours, and then it is difficult to distinguish each series. It is usually accompanied with continual oscillations having the period longer than 10 seconds, which are probably pc, their amplitude being larger than that of the main oscillation on the induction magnetogram. But, oscillations or sequence of pulses having the period of several ten seconds, can be found. This is why they are called "pt-like" pulsations. They are not attached to the class "pt" because of difficulty to distinguish individual series of limited duration.

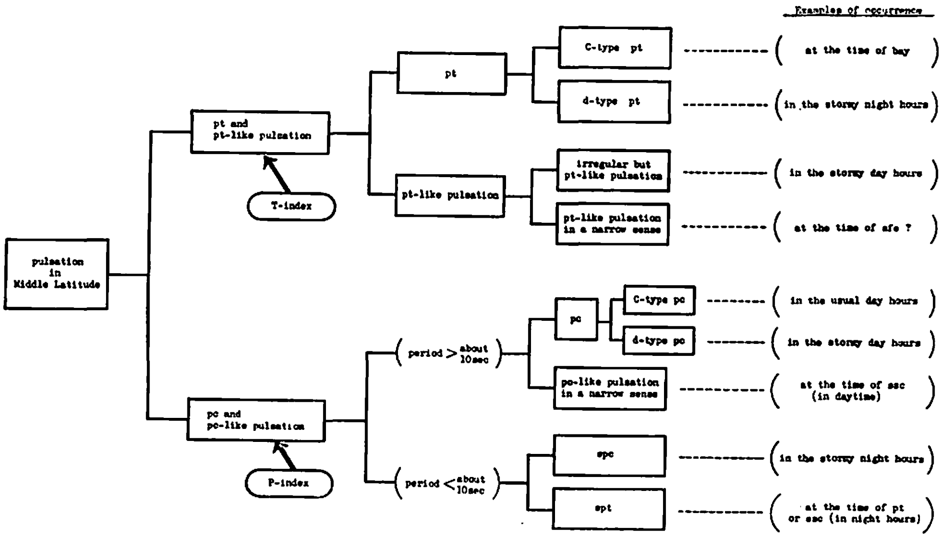


Fig. 37. Classifiication of pulsations.

Besides these three classes, other pt-like pulsatoins can be also found on the record. But they are transient phenomena which occur rarely. For example, the pulsation accomanying geomagnetic solar flare effect reported by Y. Kato and others (1959) is the case. In the above classification, the essential characters of pt or pt-like pulsations are as follows :

pt or pt-like pulsations : They have the fundamental oscillations (or sequence of pulses) having periods of several ten seconds, their forms being not regular but rather pulsative.

Opposite characters are taken as the criteria for pc or pc-like pulsations.

pc or pc-like pulsations : They are oscillations having periods less than several ten seconds (about 50 sec), their forms being regular or sinusoidal.

The character of having a considerable element of continuity is not essential in the case of pc-like pulsations. And then pc-like pulsations lasting for periods of not more than one hour can be found on the record. For example, oscillations accompanying sudden commencements of storm or sudden impulses are the case. The criteria have no limit on short side of period, then spt in § 3. 5 is also attached to this category.

The category, pc or pc-like pulsations, can be divided roughly into two sub-groups. One is the oscillation having periods between 10 and 40 seconds, which is "pc" or "pc-like pulsation" in a narrow sense. The other is the oscillation having periods less than about 10 seconds, which is "spt" for the short duration or "spc" for long duration. Spc here named has the similar character to pc except its period. In continuation of pc in the daytime, spc often occurs in night hours. Oscillation accompanying ssc or si in the daytime is pc-like pulsation in a narrow sense. And that in the night hours is spt.

The pc's are divided into two groups, as pt's, that are calm-type pc and disturbance-type pc. These sub-groups will be discussed in § 5. 1.

Chapter 4 Pulsations pc

§ 4. 1 Diurnal variation of activity of pc and spc

Differing from pt, many observers agree with each other as regards the diurnal variation of occurrence frequency of pc. Occurrence frequencies of pc counted from the quarterly list of geomagnetic variation reported by the IAGA show day time maximum for the almost all stations.

The occurrence frequency, such as numbers of hour occupied by pc, is not sufficient to express its activity. First step to improve the situation is to use a weighted frequency. Hourly weighted frequencies of pc observed at Memambetsu in the year 1958 by the induction magnetograph are shown in Fig. 38. More detailed study of weighted frequency is working by H. Oshima in the way of index, his preliminary result of diurnal variation being reproduced here in Fig. 39. It shows the mean diurnal variations of the hourly sum of his P-index at Memambetsu given for 4 months in the IGY period. The P-index is the 10-class-measure given for the each 5 minutes interval by the suitable criteria of the amplitude of pc.

Both the diurnal variations of weighted frequency and P-index have their maximum activities at morning. Occurrence frequencies observed at the other observatories show also the similar diurnal behaviour, especially for the morning high activity. The world-wide distribution of the diurnal variation of occurrence frequencies was studied by few authors (for example J. A. Jacobs and K. Sinno 1959). But simple occurrence frequency, such as hour numbers occupied by pc, is likely to misslead as to the detailed character, because it is very difficult even by the well trained observer to decide suitably and accurately the quality and the time of beginning and ending of a pulsation pc which continues intermittently for long period with developments or declines in some time of the period. To avoid this difficulty, studies using the P-index are working now by the author and H. Oshima. Besides this difficulty, the probable existence of the local pc (S. Utashiro, 1959) and spc complicate the description of the diurnal variation.

In the night hours, pc's scarcely occur as it is shown in the diurnal variation, but spc's occur most frequently in that hours. Transition from pc to spc at evening

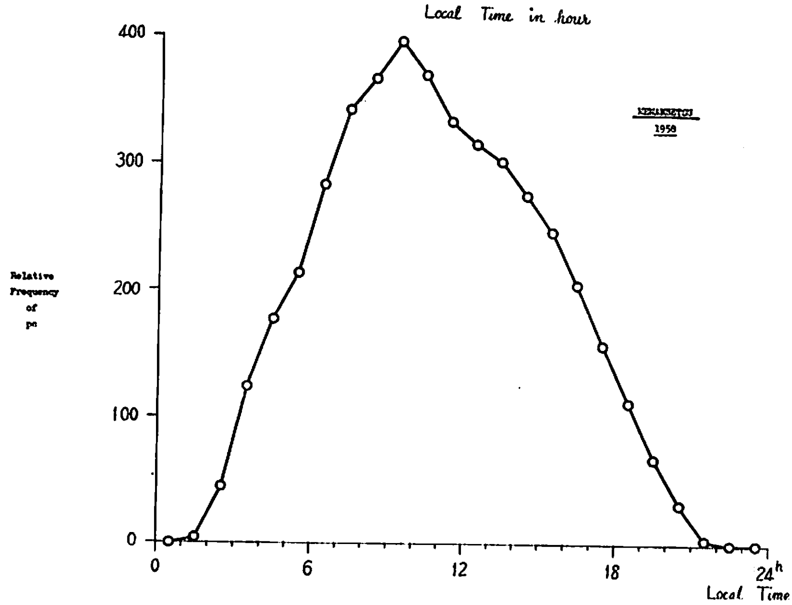


Fig. 38. Weighted hourly occurrence frequency of pc observed at Memambetsu in the year 1958.

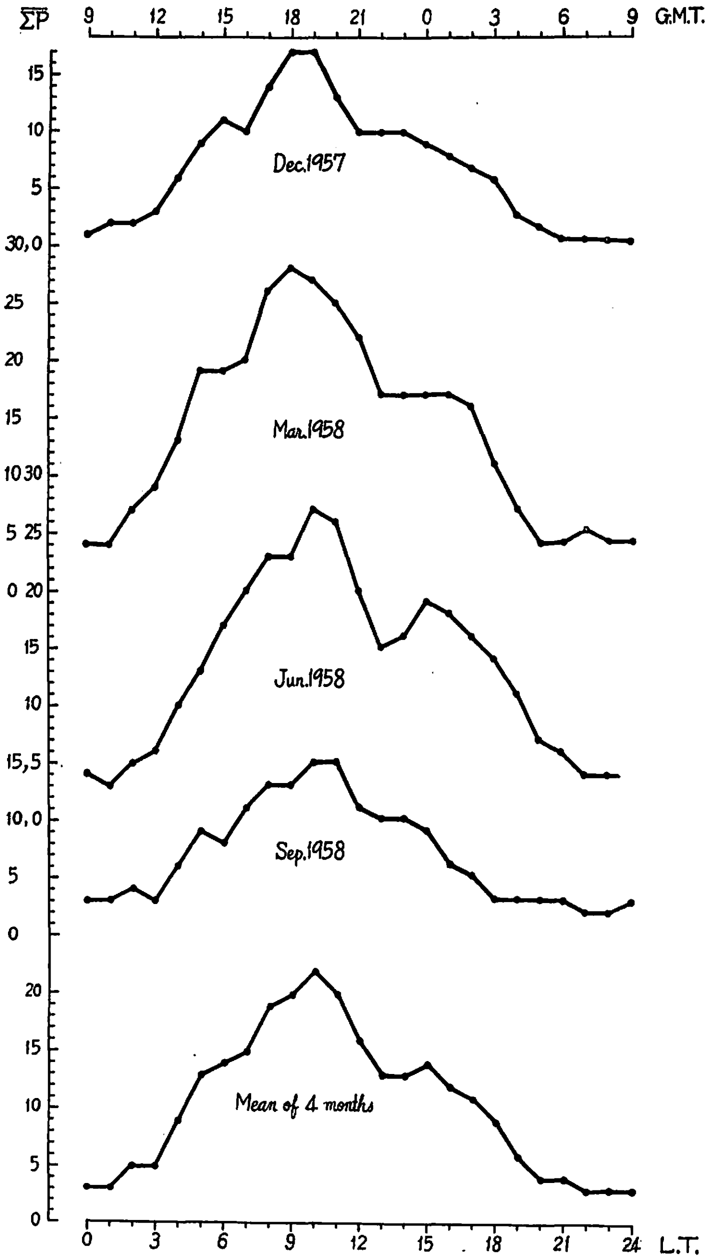


Fig. 39. Diurnal variation of P-index for the activity of pc observed at Memambetsu after H. Oshima.

or from spc to pc at morning occurs gradually in general.

In the case of the long continuing regular oscillations through day and night, such as regular pulsations in the storm time, pc goes to spc gradually at evening

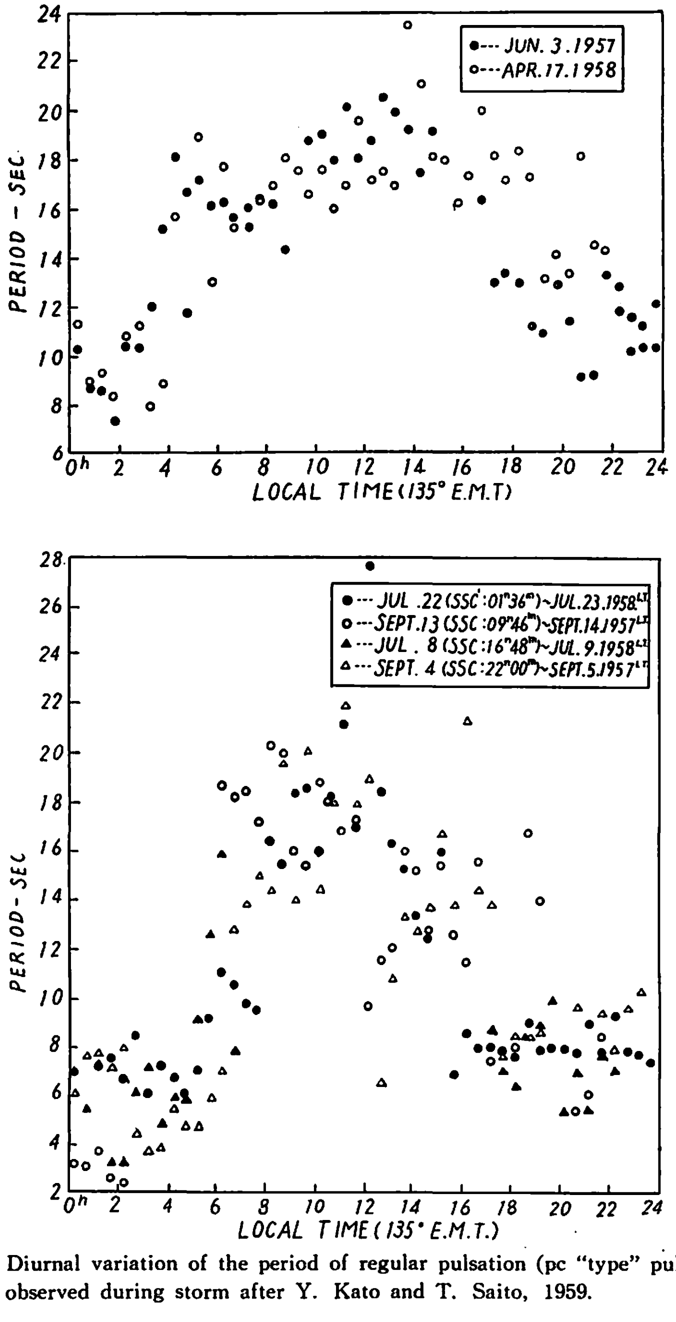


Fig. 40. Diurnal variation of the period of regular pulsation (pc "type" pulsation) observed during storm after Y. Kato and T. Saito, 1959.

and spc to pc gradually at morning. Since their transitions are usually gradual, it is difficult in general to accurately count the hours occupied by pc for the whole duration. Y. Kato and T. Saito (1959) study the diurnal variation of period of the oscillation in the time of storm. Their "pc" having the period shorter than 10 sec in the night hours seems to be the same as spc in the term of this paper.

Hereupon, it is an interesting subject to be studied whether spc is mere a kind of pc or a member of the more substantially different genus. If spc is a mere kind of pc, the lower limit of period, about 10 sec, in the criteria of pc is to be changed. As for the gradual transition from pc to spc or from spc to pc, it may be concluded that spc is a mere kind of pc with a varying period by "some" cause. On the other hand, there are some reasons that spc may be distinguished from pc.

(i) spc sometimes occurs in the night hour independently of daytime-pc.

(ii) Two groups of period are distinguished in the daily variation of the period of oscillations at the time of magnetic storms. For example, the Kato's result reproduced in Fig. 40 shows the first group centred at about 18 sec. and the second at about 10 sec. The first group is pc and the second is spc.

(iii) Surveying the record in the transition period in detail it is often possible to determine accurately the time of ending (or beginning) of pc having longer period, such as 20 sec, and the time of beginning (or ending) of spc having shorter period, such as 8 sec, though spc overlaps on pc in the transition period, and then

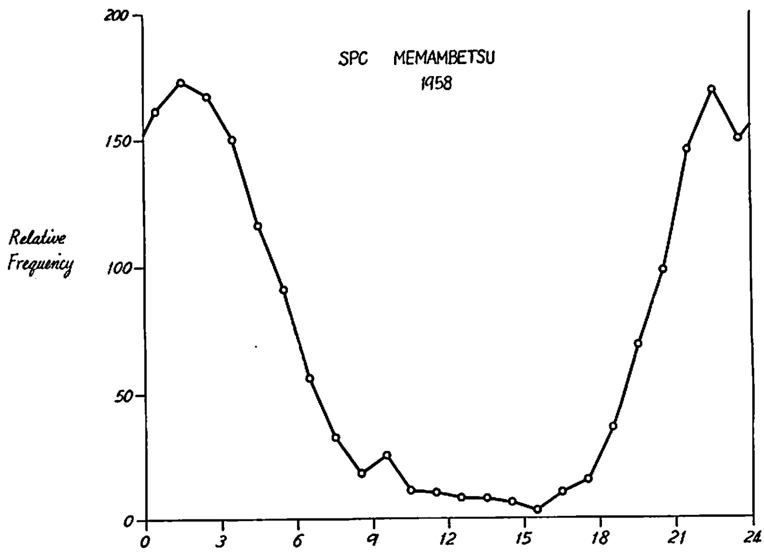


Fig. 41. Diurnal variation of weighted occurrence frequency of spc observed at Memambetsu.

the transition appears to be gradual. This tendency becomes more clear at the northern station than at the southern station.

The data of pc used in the diurnal variation of weighted frequency at Memambetsu shown in Fig. 38 is "pure pc" not containing spc. The diurnal variation of weighted occurrence frequency of spc at Memambetsu in the year 1958 is shown in Fig. 41.

§ 4.2 Annual and 11-year variation of pc

The annual variation of occurrence frequency of pc observed in the earth-currents at Kakioka for 20 years is presented in Fig. 42 (K. Yanagihara, 1957). Equinoctial maxima are the essential features of the figure, and the minimum at early winter is the second feature. Since the severe criteria for amplitude is used, the selected pc's are very active and often occur at the time of heavy magnetic disturbances. Then the feature of the equinoctial maxima is very conspicuous.

The annual variation of more general pc's containing smaller ones is shown in Fig. 43 manifests the maximum in early summer or late spring andthe minimum in early winter. The figure shows the weighted sums of hours occupied by pc taken from the induction magnetograph at Memambetsu in the year 1958. The weight 3, 2 and 1 are given for quality A, B and C which correspond "distinct", "fair and ordinary"

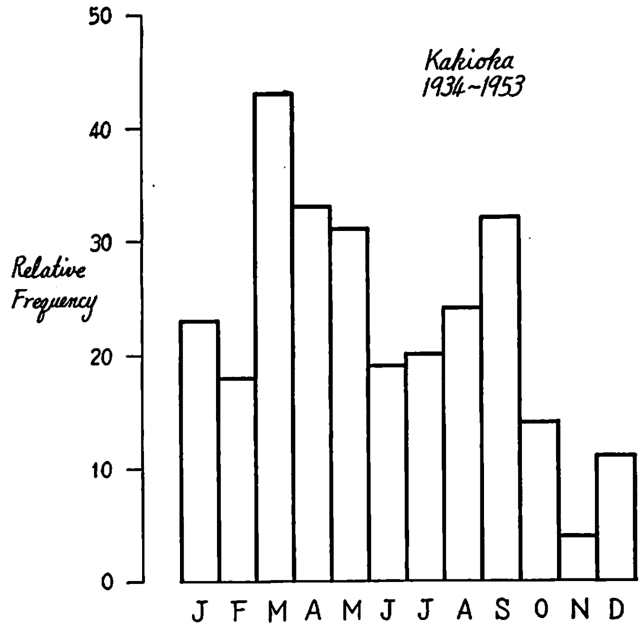


Fig. 42 Mean annual variation of occurrence frequency of pc for 20 years observed at Kakioka.

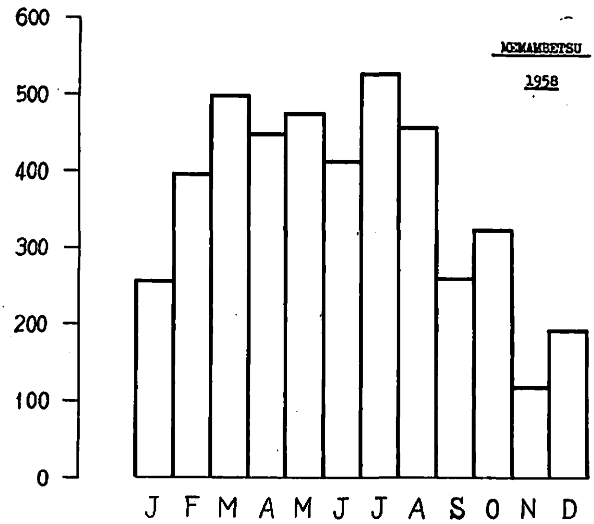


Fig. 43. Annual variation of occurrence frequency of pc for the year 1958 observed at Memambetsu.

and "doubtful" phenomena, respectively.

Comparing the Fig. 42 with Fig. 43, it is deduced that the minimum in early winter and the maximum in early summer are the substantial features of the annual variation of occurrence frequency of pc, and the equinoctial maxima occur apparently by using the data of very active pc only which frequently occurs at the time of magnetic disturbances.

The character of the low activity in winter for pc is the exact reverse to the character of pt which have the high activity in that season.

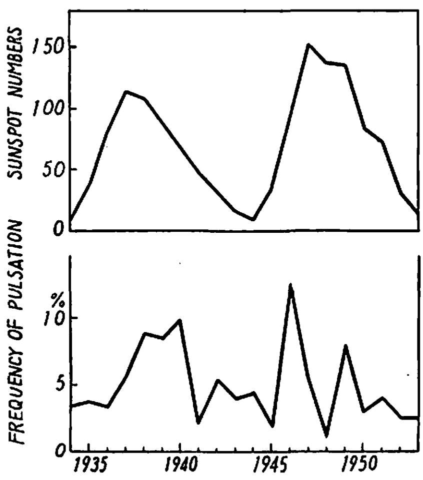


Fig. 44. Year to year change of occurrence frequency of pc.

The 11-year variation of occurrence frequency of pc is given in Fig. 44 using the data of the earth-currents at Kakioka for 20 years. The criteria for selection are the same as used for the annual variation in Fig. 42. As it is expected, 11-year variation is rather parallel to that of the relative sunspot numbers.

§ 4.3 Geomagnetic disturbance and pc

It is generally known that pc frequently occurs at the time of magnetic disturb-

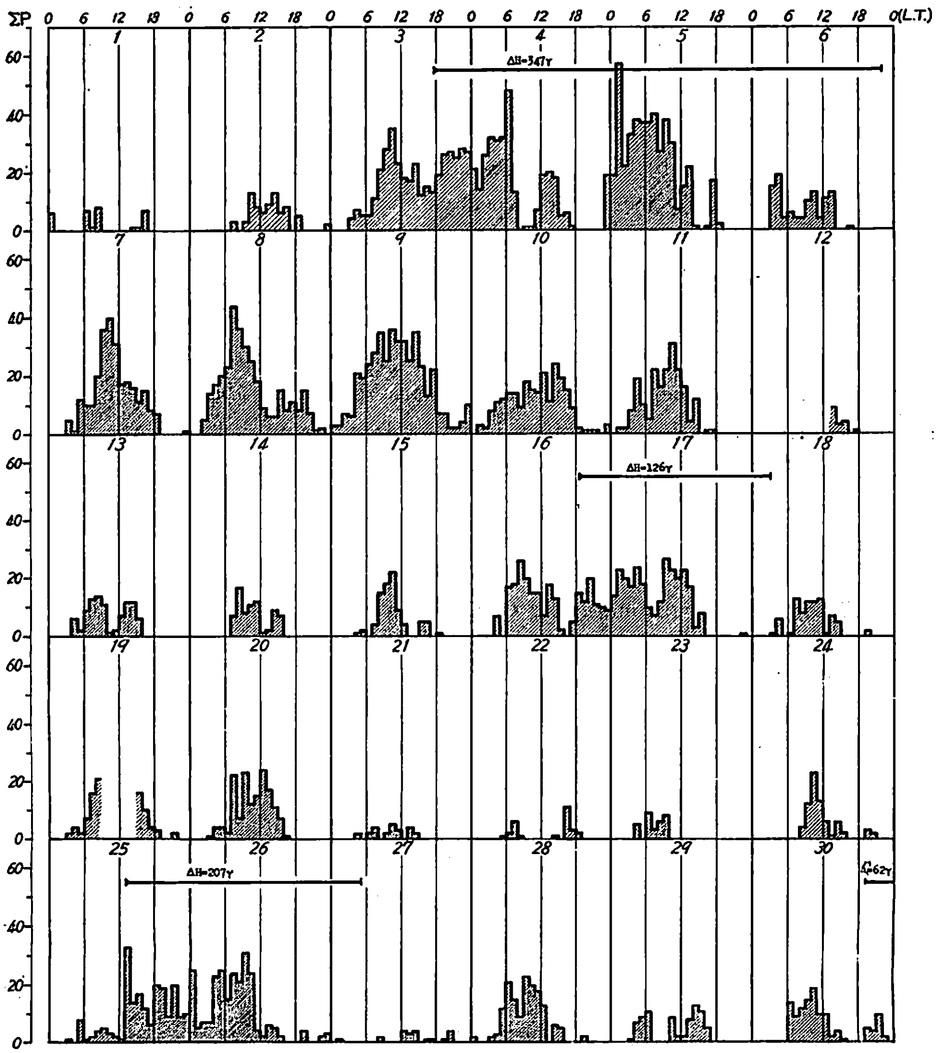


Fig. 45. P-index during September in 1958. The storm period is expressed by the horizontal line with the maximum range of H, ΔH.

ances or storms. And in detail, it is sometimes experienced that after the period of the most severe disturbance pc still continues for one or two days. Statistical tests for this situation have been given by some authors (G. Angenheister 1954, T. Yoshimatsu 1959). They show using the superposed epoch method that the maximum of K occurs one or two days before the active occurrence of pc.

On the other hand, since the occurrence frequency of pc varies considerably according to the local time, there may be the error of about one day in the time accuracy of the change of daily occurrence in relation to the variation of the other phenomena. Diurnal variation of P-index which represents the activity of pc repeats every day with a considerable range in no special reference to geomagnetic high activity (Fig. 45). At the same time of the commencement of magnetic storm, P-index increases suddenly from the diurnal value of that time. And the increased value decreases gradually in one or two days.

The storm time variation of pc is superposed on the diurnal variations as the variation of magnetic elements during storm. According to the local time of commencement of magnetic storm, the curve of the hour-to-hour change of P-index for pc-activity presents the variety of forms.

Differing from the variation of magnetic elements, the range of general or calm day's diurnal variation of P-index is rather large compared with the storm time variation. With the development of magnetic storm this diurnal variation grows large in some case, but in many cases the diurnal variation seems to be not changed by the magnetic storm.

Chapter 5 Hydromagnetic Oscillation as a Cause of Pulsations

§ 5.1 Some reviews of variation of pt and pc

Typical occurrence of pulsations in the middle latitudes is labeled as pt or pc. More complex but related genera were discussed and arranged according to their general features in § 3.6. The pulsations observed at the station in the middle latitude zone are belonged to one of the classes discussed in that section.

It is useful for understanding of characters to distinguish the pulsations which occur in calm period from that occur in disturbed period, as the distinction is generally used for the analysis of magnetic variations. From this point of view, the classes discussed in § 3.6 and presented in Fig. 37 are rearranged as follows,

(i) Calm-type pulsations

(a) calm-type pt

(b) calm-type pc

(c) spc (calm-type only)

(ii) Disturbance-type pulsations
  (a) disturbance-type pc
  (b) irregular but pt-like pulsation
  (c) disturbance-type pc
  (d) spc (disturbance-type only)
(iii) Pulsations associated with the other special phenomena
  (a) pt-like pulsation in a narrow sense
  (b) pc-like pulsation in a narrow sense
  (c) spt

The calm-type pulsations also occur more actively in the rather "disturbed" period as it is presented in the curve of occurrence rate for Kp. And this is an evidence for their relation to the solar particles. But for the period of the most severe disturbance, such as storm, observed characters of pulsations are different. They are the disturbance-type pulsations. Though spc's were not divided into two groups, calm-type and disturbance-type, in § 3. 6, because of the few results of their analysis, it is supposed by the analogy to pc that the division can be also applied to spc.

The third group pulsations are transient phenomena accompanying the special variation, such as ssc, sfe or pt.

(A) Diurnal variation

The diurnal maximum activity of calm-type pt is found near the local midnight, whereas that of calm-type pc occurs at about 9 h LT. Mean daily activity of the calm-type pt is very small compared with that of the disturbance-type pt and the irregular but pt-like pulsations, as it is shown in the time sequence of T-index which is the measure of the activity of the calm and disturbance-type pt and the irregular but pt-like pulsations. On the other hand, the diurnal variation of the

Table 3. Some characters of calm-type and disturbance-type pulsations

	Diurnal variation	Annual variation	11-year variation
Calm-type	max. activity	max. activity	
c-type pt	20h-24h LT	(early) winter	inversely proportional
c-type pc	8h-12h LT	(early) summer	proportional
Disturbance-type			
d-type pt and irregular but pt-like pulsation	7h LT or 22h GMT?	equinox	proportional
d-type pc	9h LT	equinox	proportional to variation of solar activity

calm-type pc has the range of comparable order to that for disturbance-type pc.

Occurrence time for the diurnal maximum activity of disturbance-type pt or pc is not well known, because of few analyses. Occurrence time of the diurnal maximum activity of T-index is found at about 7 h LT at Memambetsu, but the occurrence seems to depend upon GMT. It is very difficult to derive the diurnal variation of the disturbance-type pc from the complex data, because the diurnal variation has the same order or smaller range compared with that for calm-type pc or the storm time variation of disturbance-type pc. But it can be said that in night hours pc or pc-like pulsation (in a narrow sense) scarcely occurs irrespective of its type, whereas spc or spt predominates.

(B) Annual variation

Calm-type pt is active in winter months. On the contrary, calm-type pc occurs frequently in summer months. As to the disturbance-type pulsations, the active occurrence is found in equinox for both pt and pc.

(C) 11-year variation

For the calm-type pt only, the 11-year variation is anti-parallel to that of the relative sunspot numbers. The activity of the calm-type pc and the all disturbance type pulsations varies generally in parallel with the solar activity during the 11-year cycle.

§ 5.2 Outer atmosphere and hydromagnetic oscillations

Ionized particles in the atmosphere beyond the ionospheres decrease upwards in general and gradually merge in the interplanetary space. Recently, the result of observation of zodiacal light or whistling atmospherics has brought in our hand the evidence and some quantitative knowledges of the ionization in such transition region. According to these results, electron or proton density far beyond the earth surface has been estimated at several hundreds per cubic centimeter.

Relative motion between the earth which has the magnetic field and the interplanetary ionized gas forms a "cavity" surrounding the earth within which the geomagnetic field is confined. Its typical occurrence known from old times is found at the time of magnetic storm as the Chapman and Ferraro's cavity. In the period having no magnetic storm, the cavity is also possibly existing by the earth orbital motion or the other processes (T. Tamao 1959). The space in the cavity is the outer atmosphere, its radius being 6 to 10 times the earth radius.

In the ionized region, such as the outer atmosphere, some disturbances will excite the hydromagnetic oscillations. Thus, a disturbance due to the invasion of the solar particles will excite the hydromagnetic motion in the outer atmosphere and propagate downwards as the hydromagnetic waves.

In the ionized gas, three modes of hydromagnetic wave can be considered under the existence of magnetic field. One is the transverse mode which was suggested first by Alfvén, that is the Alfvén wave. The Alfvén wave propagates along the magnetic line of force, with the velocity V_A,

$$V_A=H/\sqrt{4\pi\rho},$$

where H is the external magnetic field and ρ the density of the ionized gas.

In the wave whose wave normal has the direction inclined at an angle θ to the magnetic field H, there is one mode of purely transverse wave, which has the wave velocity $V_A\cdot\cos\theta$. Besides this wave there are two other modes which are generally neither purely transverse nor purely longitudinal. Their velocities V are given by

$$V^4-V^2(V_S{}^2+V_A{}^2)+V_S{}^2\cdot V_A{}^2\cdot\cos^2\theta=0,$$

where V_S is the sound velocity. One value of V is larger than V_S, and the wave for this velocity is called the modified Afvén wave. The other is the retarded sound wave which has the small velocity V.

In the case that the wave normal is perpendicular to the magnetic line of force, the Alfvén wave and the retarded sound wave do not exist and the velocity of the modified Alfvén wave, V_m, is given by

$$V_m=\sqrt{V_A{}^2+V_S{}^2}.$$

This wave is longitudinal. In our outer atmosphere the pressure of the ionization is much less than the magnetic pressure. Then, $V_S\ll V_A$ and

$$V_m\fallingdotseq V_A.$$

According to J. W. Dungey (1958), the attenuation of the hydromagnetic wave in the outer atmosphere by viscosity is not large and the region may therefore be expected to have resonant modes of oscillations of the type described by standing Alfvén waves. The time required to travel for a distance of 10 earth radii with the velocity 40 km which corresponds to the Alfvén wave velocity when $H=30\gamma$ and the number density of proton is 300 cm^{-3} is 25 minutes. Then the observed pulsations having the period of the order of 1 minute are tentativety identified with the higher order modes of the outer atmospheric resonant oscillation.

The equations of hydromagnetic oscillations in the outer atmosphere was given by him under the particular conditions. For the special case, coupling of the two modes of oscillation is loosened or severed. One mode is the toroidal oscillation, and the other is poloidal. These oscillations corresponds to the Alfvén wave and the modified Alfvén wave respectively. The rough estimates of the eigen period of the oscillations were given by Y. Kato and T. Watanabe (1957) using eigenvalue theorem and by T. Obayashi (1959) using the double traverse time of the waves.

The estimation of the period of hydromagnetic oscillation in the outer atmosphere largely depends upon the supposed physical state of the space. If the ion density gradually decreases from the ionospheric value to the interplanetary value of 600 cm^{-3}, which was given by the observation of the zodiacal light, more or less according to the Dungey's distribution, $N=N_S \cdot \exp(2.5\, r_0/r)$ and the supposed radius of the cavity is 10 times the earth radius, the period of double traverse of the modified Alfvén wave has considerably large values compared with the period of the ordinarily observed pulsation at the middle latitude station because of the small value of the (modified) Alfvén wave velocity in the upper part of the cavity. To get the adequate value of the period for pulsation, it is necessary to suppose that the cavity has a smaller radius which is about 4 - 6 earth radii or that the ion density in the upper part of the outer atmosphere is much smaller than the value of the interplanetary space, 600 cm^{-3}.

As the N_S - value in the Dangey's distribution of ion density in the outer atmosphere, somewhat small value of 10 cm^{-3} will be supposed here instead of 600 cm^{-3} of the interplanetary space. This small value is consistent with the result of nose whistler by R. A. Helliwell and others (1956). This distribution is applicable only for the upper part of the outer atmosphere. Up to the middle of the region, somewhat different distribution, such as that given by K. Maeda and I. Kimura, is reasonable. But the estimate of the period is not so seriously altered by the adoption of different distribution for the lower part of the outer atmosphere, because the low value of the modified Alfvén wave velocity occurs in the upper part of the region. For the outer atmosphere having 8, 9 and 10 earth radii, the periods necessary for the modified Alfvén wave to travel the space are about 75, 120, and 180 seconds, respectively. These periods are roughly coincident with the observed period of pt-type pulsations.

Pc-type pulsations are more regular than pt and they have shorter period, 10 - 40 sec. Then it is necessary for the cause of pc-type pulsation to consider the more complete standing oscillation in the more limited space.

§ 5.3 Maximum zone of Alfvên wave velocity and formation of standing oscillation in lower part of outer atmosphere

The Alfvén wave velocity reaches the maximum value at some thousands km height. It has been pointed out by A. J. Dessler (1958) that the downward travelling hydromagnetic wave will be reflected back at this zone. Possibility of the formation of standing oscillation in the lower part of the outer atmosphere below this zone was suggested recently by some authors (T. Watanabe 1959, T. Obayashi 1959 and K. Yanagihara 1959).

For an axis-symmetric case, the resonance oscillation was studied in detail by T. Watanabe. From the diurnal variation of observed periods of regular pulsations, however, the existence of the distinct latitudinal change for period can be deduced.

Then, the non-symmetric case is to be considered, at least for the discussion of period. But since the non-symmetric case is difficult to treat mathematically, the rough estimate of period of standing oscillation will be given by calculating the time necessary to travel in the region.

The distribution of the Alfvén wave velocity for height depends largely upon the distribution of ionized gas density. The data used by Dessler have shown the maximum Alfvén wave velocity at about 1000 km height. On the other hand, it was reported recently that the electron density up to 600 km height and its extrapolation up to 3000 km level were calculated from the data of the artificial satellite in USSR, Sputnik I (1958). The electron density formula for vertical distribution by Sputnik bears a striking resemblance to that obtained by K. Maeda and I. Kimura (1956) using the whistler data. By the distribution, the maximum Alfvén velocity is given at about 3000 km height. Using the Maeda and Kimura's model for the vertical distribution of electron density, the travel time in the equatorial plane is given as follows :

$$2 \cdot \int_{300\text{km}}^{3000\text{km}} \frac{dh}{V_A} = 20\text{sec}.$$

§ 5.4 **Hydromagnetic oscillations and pulsations**

In a cavity which is formed by the interaction of the earth's magnetic field and the interplanetary ionized gas, hydromagnetic oscillations may possibly be excited by the disturbance given by the impinging of the solar particles as stated in the preceding two sections. Toroidal oscillation, which is one mode of them, will give rise to the pulsation in the higher latitude, and then it will not be discussed here. Polloidal oscillations in the whole cavity have eigen period of the order of 1 minute, which is adequate for pt's period, under the suitable condition of the physical state of the outer atmosphere. On the other hand, the same mode oscillation in the lower part of the outer atmosphere may give rise to pc-type pulsation whose period is shorter than pt.

As it has been pointed out by Dessler, the zone where the Alfvén wave velocity is maximum reflects the hydromagnetic wave, and then the grouth of hydromagnetic oscillation in the whole cavity is prevented. The pt-type pulsation has hereby the feature of rapidly damping and rather irregular form of oscillation. The more the reflection by the zone is effective, the more the standing oscillation in the lower region for pc is suitable to develop. Thus, the feature of pc (for calm period) is diametrically oppsite to that of pt for calm period, as it is presented in the Table 3. For the disturbed period, however, the behaivour of the disturbing agent overcomes the condition and then the different aspect can be seen as it is shown in the feature of disturbance type pt and pc.

When the cavity encounter a dense region of the interplanetary ionized gas, the disturbance due to collision will propagate downwards as hydromagnetic wave and will excite the standing oscillations in the lower part of the outer atmosphere. If the dense ionized gas has no relative motion to the sun, its first encounter with the earth's outer atmosphere will occur at about 6 hour's meridian of the earth. And as the earth orbital motion proceeds, it will envelope the earth's outer atmosphere with the top at 6 hr. If the dense region is a solar corpuscular stream or cloud with the velocity of the order of 1000 km/sec, the cavity will be deformed. The cavity in this case is the Chapman and Ferarro's one which has the top at about noon. Then, it is reasonably explained that pc's are most frequently observed at 6 hr to 12 hr. This feature is presented in the diurnal variation of pc.

In these day hours, the reflection is nearly complete at the zone where the Alfvén wave velocity is maximum, and then the standing oscillation in the lower region is distinct and the oscillation of the whole cavity is not effective. In terms of observed phenomena, pc's are active whereas pt's are not active.

The impinging solar particles which give rise to a bay disturbance will excite the incomplete hydromagnetic oscillation in the night side of the cavity, because the inner reflection is not complete in that side. Then, pt's are frequently observed at night hours. Spt accompanying pt is the oscillation excited in the lower region by the same agency. Its period shorter than pc is explained by the decreased density of ionized gas in that region, as it is discussed in the preceding section. Rather irregular features of oscillation for pt are due to the incomplete reflection at the zone where the Alfvén wave velocity is maximum.

Accompanying ssc, spt or pc-like pulsations are observed. Main variation of ssc hydromagnetically propagating downwards in the outer atmosphere will excite the oscillation in the lower region below the inner reflecting zone. This is the cause of the spt or pc-like pulsations accompanying ssc. The spt (pc-like pulsation) is observed in the night hours (daytime), as it is expected. The existence of pt-like pulsation accompanying ssc is also found in some cases. Though ssc's occurred in the night hours may always be accompanied with pt-like pulsations, it is difficult to find the evidence in the record because of the difficulty to distinguish the phenomenon from the main variation of ssc. Oppossite characters of calm-type pt's to those of calm-type pc's in diurnal, annual and 11-year variations are caused by the exclusive excitation of hydromagnetic oscillation due to the reflection at the zone of maximum Alfvén wave velocity.

In the night time, in winter or sunspot minimum years, the reflection is not so effective that pt's are predominate. In the daytime, in summer or sunspot maximum years, on the other hand, pc's are active because the reflection is effective enough.

Why the reflection power changes in such a manner is a difficult problem to explain in the present status of knowledge of the outer atmosphere. But some possible qualitative approach will be given in the following.

The decrease of the Alfvén wave velocity may be gradual above its maximum zone. Then, the reflection power is roughly represented by the difference between the values of the Alfvén wave velocity at its maximum and its minimum which occurs at F_2–layer, the zone of maximum electron density. The difference depends upon the gas density in the region, provided that the outer atmospheric gas density in the region far beyond the earth is not changed. The gas density in the region from the ionosphere up to some thousand kilometers height may probably change with time roughly in the same manner as in the upper ionosphere. Thus, in the daytime, in summer and sunspot maximum years the gas density of the region is increased, and the difference of the Alfvén wave velocities becomes large. As the result, the reflection becomes effective.

In the period of heavy disturbances, the variation of activity of pulsations has somewhat different features, because the variation of the agency which excites the hydromagnetic oscillation plays an important role. The power or frequency of the agency may change with time in a like manner as general magnetic disturbances. This is observed in the time–variation of disturbance–type pc and pt as presented in Figs. 32, 33 and 45. The maximum in the equinoctial months or sunspot maximum years are explained by the reason that the general magnetic disturbance is maximum in that period. Though the variation of agency is to be taken into consideration also for the description of the variation of calm–type pt or pc, but the result of such consideration brings only a slight modulation for the change. For example, the longitudinal inequality of the diurnal variation of pt–occurrence is the case. This is an effect of GMT change of the impinging solar corpuscles which suffer the influence of the earth magnetic field.

Concluding Remarks

In this report the classification, characterization and their interpretation of geomagnetic pulsations observed at middle latitudes are given using the International Geophysical Year data. Pulsations pt and pc which have been world–widely introduced since the meeting at Copenhagen are most prominent and typical ones on the record, though some careful considerations for the observation method having proper frequency response are necessary to distinguish them. More general pulsations with ambiguous character are also found often on the record. In the magnetically disturbed period, so–called "disturbance–type pulsations" are found. Another example is the shorter period oscillation spc or spt with the period less than about 10 sec.

Most of complicated and puzzling characters of pulsations reported in the pre-IGY period seem to be well interpreted by the analysis using the suitable classification for pulsations of the subject. Particular attention is to be given for the diffeerence of character between disturbance-type and calm-type pulsations such as presented in their diurnal, annual or 11-year variation. Various behaviours can be found on the variation of activity according to the relative efficiency of the primary agency or the terrestrial effect near the earth. The primary agency may play an important role in the variation of the disturbance-type pulsation. Then the annual variation of occurrence frequency of disturbance-type pt or pc shows the equinoctial maxima, whereas the calm-type pt (or pc) has the maximum activity in winter (or summer).

A fundamental division of observed pulsations is given by extending the description of pt and pc by IAGA. Though their character of "train" or "continuity" has been lost in the generalized pt and pc, it is clearly shown by many fruitful results from the analysis using the two classes that they are fundamental classes. An attempt was made for indices to express the activity of each group of pulsations independently. Though only few studies were done on the analysis using the indices, P and T, its application to the study of geomagnetic disturbances is a promising problem.

Hydromagnetic behaviour in the earth's outer atmosphere or ionosphere is not so clear with respect to pulsations. According to the increase of knowledge on the physical state of the outer atmosphere including the Van Allen bands and the deviation of the magnetic field from that due to the centred dipole, this field of study will be rapidly developed also. In the present stage, a possible cause of the pulsations is given by the hydromangetic oscillation in the suitably supposed outer atmosphere.

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