COMPARATIVE STUDY OF MAGNETIC Pc 1 PULSATIONS OBSERVED AT LOW AND HIGH LATITUDES: SOURCE REGION AND GENERATION MECHANISM OF PERIODIC HYDROMAGNETIC EMISSIONS

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***Abstract*:** Main purposes of this study are to identify the source region and generation mechanism of periodic emissions by comparison of the characteristics of emissions observed at high and low latitudes. In the present paper, the periodic emissions observed at Syowa Station and Memambetsu for a two-year period from January 1977 to December 1978 are studied. Relations of the occurrence to the magnetic activity *Dst* and also *Kp* dependence of the mean frequency are investigated statistically.

Periodic emissions are closely related to development of the equatorial ring current and tend to occur during the recovery phase of an intense magnetic storm. The occurrence peaks are observed on the second or third day after the maximum *Dst* at low latitudes, and two days later at auroral latitudes. This suggests that the occurrence depends on the conditions of the *Dst* development. The emissions are observed usually only at low latitudes in case of a sharp and distinct development of the *Dst*. While, in case of gradual storm development, the emissions occur at rather high latitudes. These results indicate that the source region of the emissions may be located near the plasmapause and that the plasmapause position shifts gradually outwards with the lapse of storm-time. In addition, the emissions are subjected to an intense attenuation through ionospheric duct propagation.

On the other hand, mean frequency of the emissions is higher at low latitudes than at high latitudes. At both latitudes the emission frequency (Hz) shows a characteristic diurnal variation with a maximum at about 06 LT, specially in disturbed conditions. These facts will support the above-described interpretation. If resonance frequency becomes lower with an outward shift of the plasmapause, the above characteristics of the mean frequency will also suggest that the source of the emissions is the plasmapause and the frequency reflects the size and the configuration of the plasmapause.

Assuming that the source region of the periodic emissions is near the plasmapause and the emissions are generated by proton cyclotron instability, the various observational facts are consistent.

1. Introduction

Pc 1 range pulsations observed at Memambetsu, Kakioka, Kanoya and Chichijima are examined regularly. These four observatories constitute a network of surface stations at low latitudes. While, similar observations at Japanese Antarctic stations, Syowa and Mizuho, are also carried out as a main project by the National Institue of

Polar Research.

Since the 1960's, the characteristics of pc 1 range pulsations have been analyzed with various types of dynamic spectral analyzers by many research workers (SAITO, 1960; HEACOCK and HESSLER, 1962; KATO and SAITO, 1964; TROITSKAYA, 1967; KAWAMURA, 1970; KOKUBUN, 1970; SAKURAI, 1975; FRASER, 1975; TOYA *et al.*, 1979; KUWASHIMA *et al.*, 1981; KAWAMURA *et al.*, 1981). Meanwhile, the theoretical studies of pc 1 pulsations have also been done by many workers. The generation mechanism in the magnetosphere has been examined by CORNWALL (1965), JACOBS and WATANABE (1966) and GENDRIN (1970). TEPLEY and LANDSHOP (1966), MANCHESTER (1966) and GREIFINGER and GREIFINGER (1968, 1973) have introduced the ionospheric duct propagation theory of the pulsations. In spite of the many research works mentioned above, several important problems remain unresolved.

There has been considerable confusion in the research work on pc 1 characteristics. It was pointed out in a previous paper (KUWASHIMA *et al.*, 1981) that pc 1 pulsations observed at auroral latitudes can be classified into three sub-groups, HM chorus, periodic emissions and others, and that about half of them are HM chorus. On the other hand, at low latitudes only periodic emissions are observed. Various differences in the characteristics of occurrence of pc 1 between auroral latitudes and low latitudes will be ascribed to the above facts.

As for the exciting mechanism of periodic emissions, a model of proton cyclotron instability was proposed by CORNWALL (1965) and by JACOBS and WATANABE (1966). In the cases where the beam velocity of trapped protons exceeds the local Alfvén velocity, hydromagnetic waves at a frequency corresponding to the cyclotron resonance are emitted. It has been suggested that the particle energy of the storm-time ring current protons is transfered to the hydromagnetic wave energy through the instability. Significant relations between the generation of the emissions and the geomagnetic activity have been reported in our previous papers (TOYA *et al.*, 1979; KUWASHIMA *et al.*, 1981; KAWAMURA *et al.*, 1981).

Another important factor is the ionospheric effect on the propagation of the waves from the source latitudes to lower and higher latitudes. According to the investigations by CAMPBELL and THORNBERRY (1972) and FRASER (1975), there is a remarkable westward propagation of waves in the ionospheric duct, while the observations by ALTHOUSE and DAVIS (1978) show that the propagation direction of the waves tends to coincide approximately with the geomagnetic meridian. Such an apparent contradiction in results should be clarified. In a previous paper (KAWAMURA *et al.*, 1981), the authors pointed out that the waves observed at low latitudes will propagate from the plasmapause latitude to lower ones through the ionospheric duct along the magnetic meridian.

In the present paper, *Dst* dependence of the emission occurrence and *Kp* dependence of the mean frequency are investigated statistically based on the data obtained at Syowa Station and Memambetsu for the two-year period, 1977–1978. The source region of the emissions will also be discussed based on the above observational results.

2. *Dst* Dependence of Occurrence of Periodic Emissions

Hourly occurrences of the periodic emissions for the period of April 1977 at Syowa Station (SYO), Woomera (WMR) and Memambetsu (MMB) are shown in Fig. 1 together with hourly *Dst*-index. The hourly occurrence means the number of 10-minute intervals during the hour in which any periodic emission is observed. Woomera (−41.°3, 211.°4) and Memambetsu (34.°3, 209.°7) are located on the same geomagnetic meridian of about 210° and also are connected with an approximate conjugate relation being located in opposite hemispheres. The local time of Syowa Station (−66.°7, 72.°4) differs by about 9 hours from that of the other two stations. As described in the previous paper (KAWAMURA *et al.*, 1981), almost the same periodic emission is observed simultaneously at both Memambetsu and Woomera. However, the probability of simultaneous occurrence between Syowa and the other two stations is very low considering the characteristics of the diurnal variation. Nevertheless, it is clearly seen in the figure that the emission appears frequently in the recovery phase of *Dst* not only at auroral latitudes but also at lower latitudes. This suggests that the occurrence of the emissions in the magnetosphere is closely connected with development of the storm-time ring current.

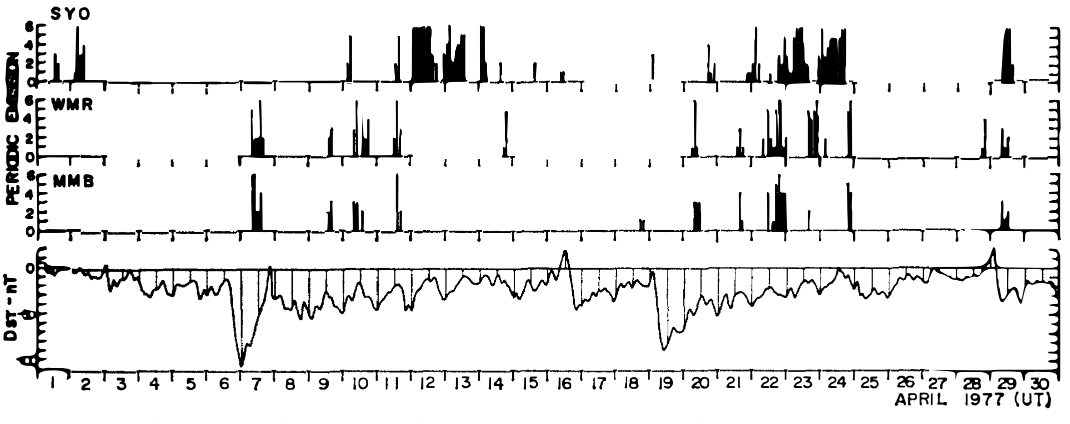

Fig. 1. Development of the equatorial ring current (Dst) in April 1977 and successive occurrence of periodic emissions at Memambetsu (MMB), Woomera (WMR, near the conjugate of MMB) and Syowa Station (SYO).

To make sure of the above suggestion the relation of occurrence of the emissions to *Dst*-index at both Memambetsu and Syowa is examined in more detail for the two-year period from January 1977 to December 1978. The results are given in Fig. 2 which shows the daily occurrences of the emissions at both stations and daily *Dst*-values. It is clearly seen in the figure that at both stations the occurrences are concentrated generally in the recovery phase which follows an intense magnetic storm. Moreover, it will be pointed out that the occurrence peak at Syowa is later, usually by one or two days, than that at Memambetsu. This gives us an important clue with regard to the source region of the emissions in the magnetosphere. As the emission may be subjected to an intense attenuation in the course of its propagation along the ionospheric duct, such a delay of the occurrence peak at auroral latitudes compared to that at low latitudes is perhaps interpreted as an outward shift of the source, the

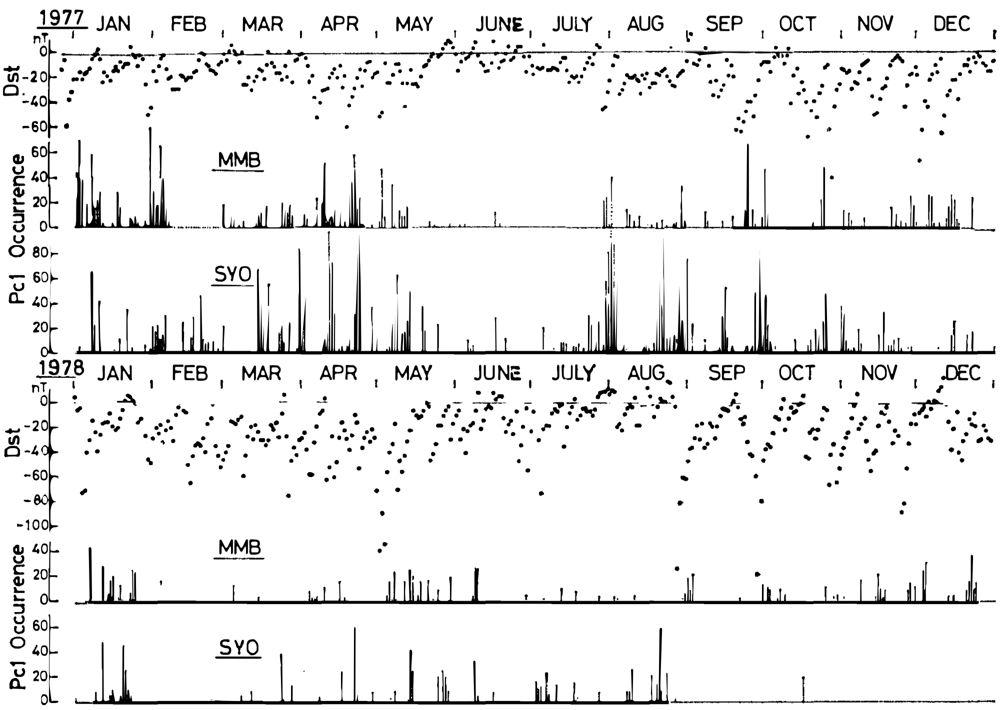

Fig. 2. Development of the equatorial ring current (Dst) and occurrence of periodic emissions at MMB and SYO during the two-year period, 1977–1978.

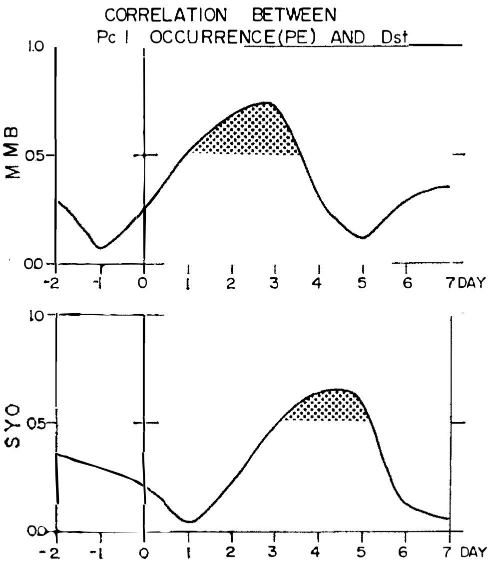

Fig. 3. Cross correlations between equatorial Dst and occurrence of periodic emissions at each station, MMB (upper frame) and SYO (lower frame).

plasmapause, which follows the recovery of storm-time *Dst*.

Cross correlations between the *Dst*-index and the occurrences of the emissions at both Syowa and Memambetsu were also investigated statistically. The results for April 1977 are illustrated in Fig. 3. The abscissa gives the number of days from the maximum of *Dst*. The occurrence at Memambetsu has a peak on the second or third day after the maximum *Dst*. At Syowa a clear peak appears on the fourth or fifth day. Similar results have been also obtained from a statistical superposition for whole period of the two years.

However, there is a curious but very important fact. It is seen in Fig. 2 that, although *Dst* activity is higher in 1978 than in 1977, the emissions are inactive in that year not only at Memambetsu but also at Syowa. This suggests that the occurrence is not only related to the development of ring current at storm-time but also there is a clear long-term variation which depends on some other causes. We will discuss the problem in more detail in a forthcoming paper.

The *Dst* dependence described above is, however, not so simple. The development of the ring current seems to result in different behaviors at the two stations.

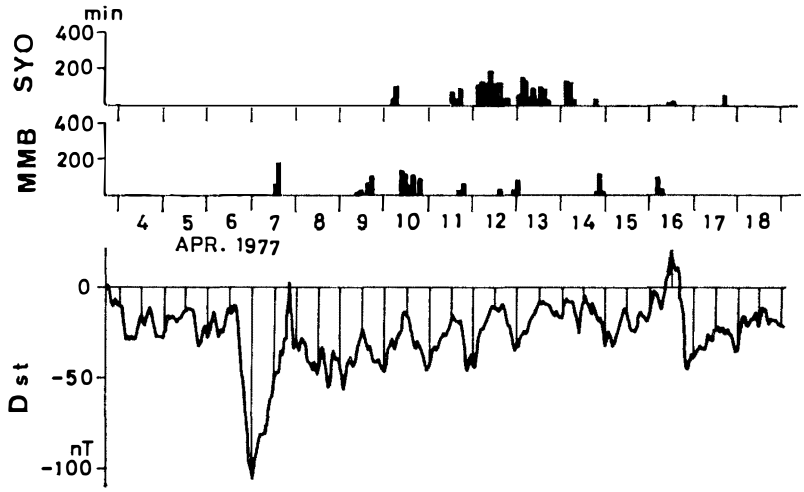

Fig. 4. Successive occurrences of periodic emissions at MMB and SYO in recovery phase of a magnetic storm of moderate intensity.

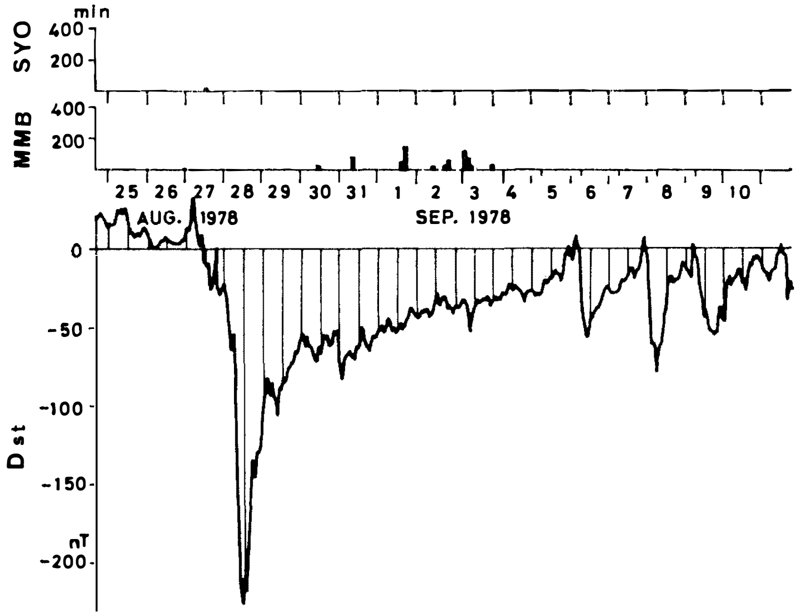

Fig. 5. Occurrence of periodic emissions at MMB in recovery phase followed by very sharp development of Dst.

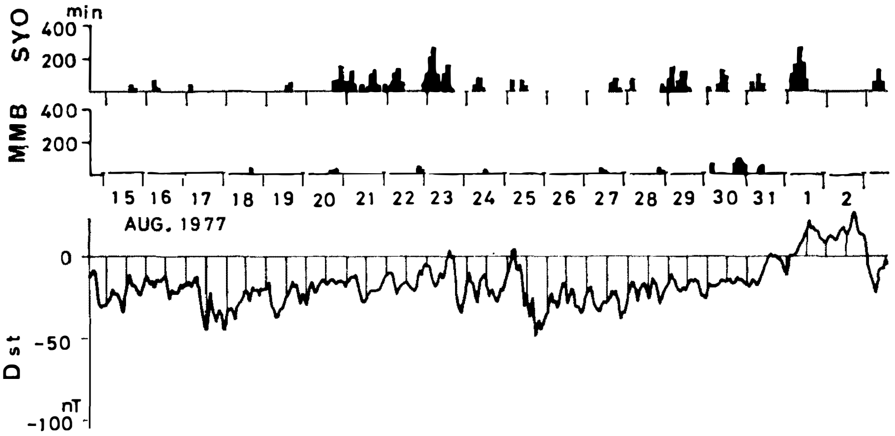

Fig. 6. Occurrence of periodic emissions at high latitudes during the recovery phase followed by a rather gradual development of Dst.

When a rather intense magnetic storm occurs and recovers gradually, the emissions appear first at low latitudes and then shift to higher latitudes. The emissions at low latitudes precede by about two days those at auroral latitudes. Such a behavior of *Dst* dependence of pc 1 emissions is one of the most typical characteristics. An example is given in Fig. 4. When the development of *Dst* is fairly active and the recovery is very sharp, the emissions are observed in general only at lower latitudes. Such a typical example is shown in Fig. 5. On the other hand, when the geomagnetic condition is not so active but variable, the emissions are observed mainly at higher latitudes. An example is illustrated in Fig. 6. Note that Syowa and Memambetsu are located in opposite hemispheres. Frequency of occurrence of the periodic emissions shows a characteristic seasonal variation. The occurrence is much higher in winter than in summer at least at middle and low latitudes, as described in the previous paper (KAWAMURA *et al.*, 1981). In comparing the occurrence between these two stations, the seasonal variation should be taken into consideration. Nevertheless, it seems that the dependence on *Dst* mentioned above is significant.

When the storm-time ring current (*Dst*) develops, of course, *Kp* activity will be also high. There is a close relation between the *Kp* and the geocentric position of the plasmapause in the equatorial plane. As is well known, the higher the geomagnetic activity-*Kp* is, the more the plasmasphere contracts to lower latitudes. Therefore, it can be proposed that the position of the source region of the periodic emissions in the plasmapause shifts to higher or lower plasmapause latitudes corresponding to the variation of *Dst*.

3. *Kp* Dependence of Mean Frequency of Periodic Emissions

Diurnal variation of the mean frequency of the periodic emissions was also statistically investigated. The results for Syowa Station are given in Fig. 7. The occurrence of periodic emissions is represented by the contours in the graph of emission frequency (Hz) versus magnetic local time (MLT). The contours represent the number of times which emissions in the corresponding mean frequency range are observed

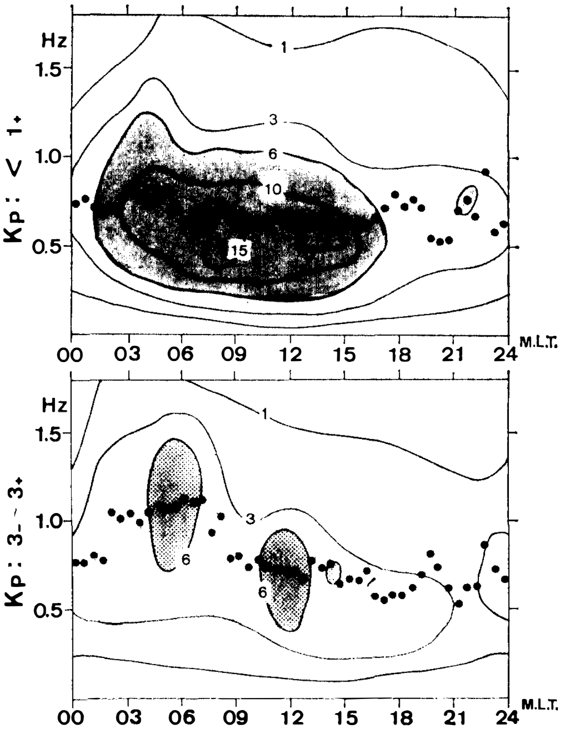

Fig. 7. Diurnal variations of mean frequency of periodic emissions observed at SYO in both quiet (upper frame) and disturbed (lower frame) conditions.

in each thirty minute interval. The darkened area gives frequency-time intervals in which the number of times of occurrence exceeds six. The solid spots give the average frequency for each time interval. As seen in the figure, during the disturbed periods (lower panel) the mean frequency shows a characteristic diurnal variation with a clear maximum above 1 Hz at about 6 h. The minimum value at aobut 18 h is at most 0.5 Hz. On the contrary, in the quiet periods (upper panel) the mean frequency is low and the diurnal variation is not sharp. These features of the diurnal variation probably reflect effects of the *Kp* on the configuration of the plasmasphere.

With a view to confirming the results described above, the local-time dependence of mean frequency of each individual periodic emission observed at each station, Syowa (upper frame) and Memambetsu (lower frame), for the same two-year period, 1977–1978, is shown in Fig. 8. The left- and right-hand circles in each frame correspond to quiet ($Kp \leqq 1+$) and disturbed ($Kp \geqq 3-$) conditions, respectively. In each circle, radial distance from the center gives the mean frequency of each emission. The center and the outer circle correspond to 2 and 0 Hz, respectively. From the figure, the same features of the diurnal variation shown in Fig. 7 are seen more clearly. Namely, the mean frequency during quiet conditions usually has a fixed value throughout the course of day. While, in disturbed conditions the mean frequency shows a distinct diurnal variation corresponding to the dawn-dusk asymmetry of configuration of the plasmapause in a storm time. Moreover, it is clearly seen that the frequency at Syowa is lower than that at Memambetsu. The frequency has a clear peak of the occurrence around 0.9 Hz at Memambetsu and around 0.6 Hz at Syowa. The results are roughly in accordance with a previous investigation of the authors (TOYA *et al.*, 1979). These facts also suggest that the source region of the emissions is located

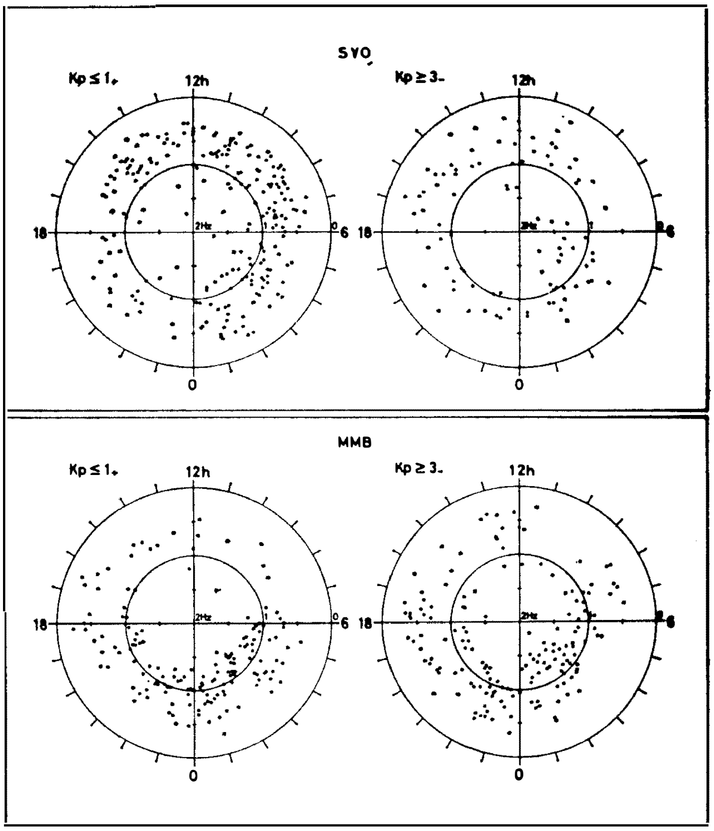

Fig. 8. Diurnal variations of mean frequency in quiet ($Kp \leq 1+$) and disturbed ($Kp \geq 3-$) conditions. Upper and lower frames correspond to SYO and MMB, respectively.

near the plasmapause and that the diurnal variation and the *Kp* dependence of mean frequency should reflect a corresponding variation of the configuration of the plasmapause in that time.

It is deduced from the above-mentioned features that the emissions are generated through a mechanism of wave-particle interaction near the plasmapause in the recovery phase of an intense magnetic storm. As is well-known, the generation mechanism can be explained by an ion-cyclotron resonance caused by ring-current protons. When the beam velocity, v, is higher than local Alfvén velocity, V_A, the resonance frequency, f_r, is given by the following relation:

$$f_r \simeq \frac{\Omega_i}{2\pi} \frac{V_A}{v},$$

where $f_i = \Omega_i / 2\pi$ is the proton cyclotron frequency. Assuming a dipole geomagnetic field and a proton energy of 40 keV, resonance frequencies for $L=3.5$ and 4.5 are roughly estimated. The results are illustrated schematically in Fig. 9 assuming plasma densities at the two values of L are 3000 and 1000/cc, respectively. Using a rough estimation, it will be understood that the mean frequency of the emissions will vary corresponding to an inward or outward shift of the source region, the plasmapause. The above statistical difference of the mean frequency of the periodic emissions between high and low latitudes suggests that the lower the plasmapause latitude is and the higher

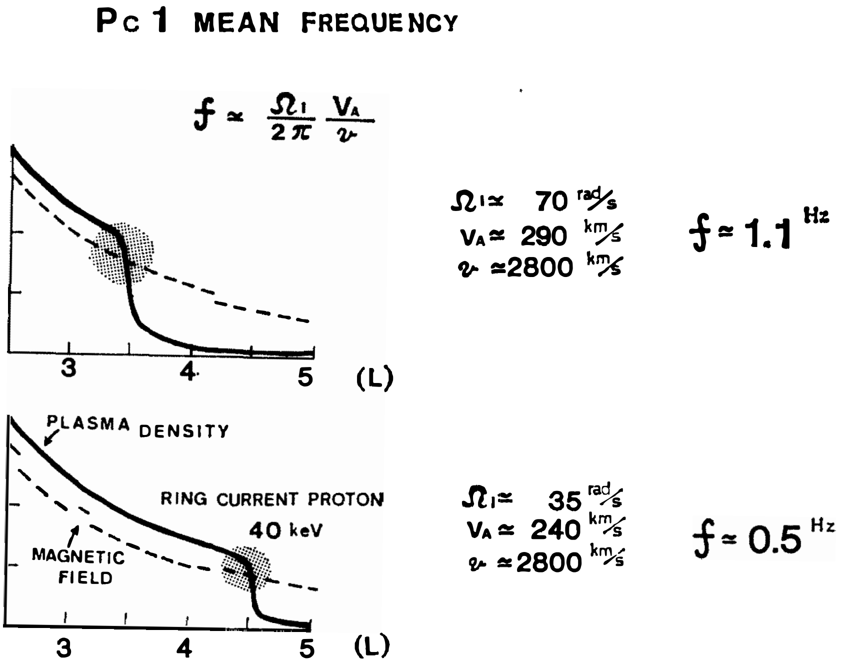

Fig. 9. Schematic illustration which shows a change of resonance frequency followed by an outward shift of the plasmapause.

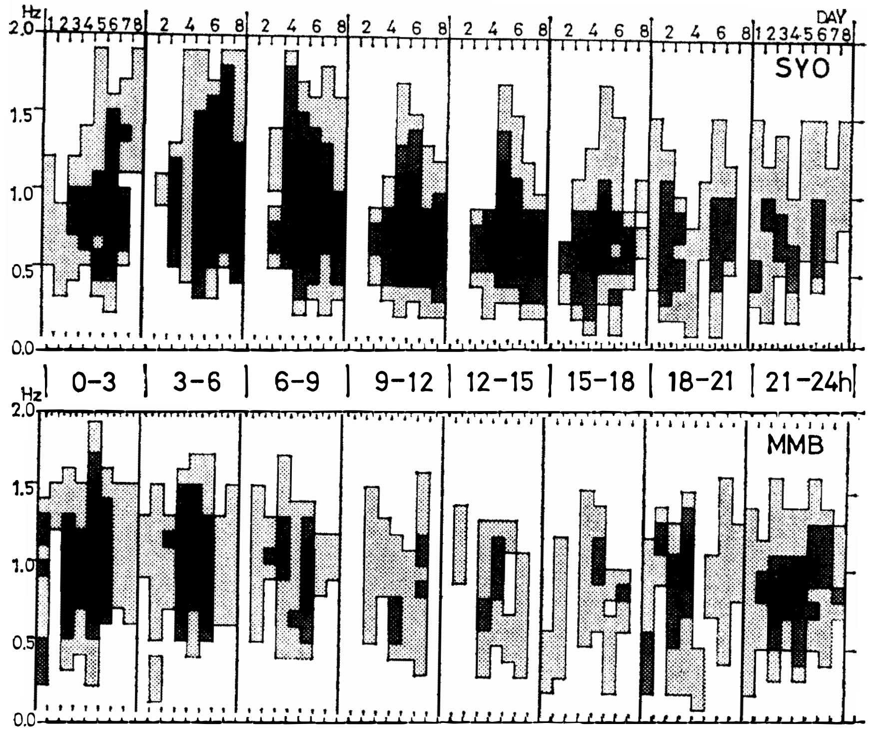

Fig. 10. Superimposed variations of mean frequency observed at SYO and MMB against storm-time and local time.

the emission frequency is, the more likely the observation of the emissions at low latitudes becomes. The *Kp* dependence and the local time variation will also reflect the configuration of the plasmasphere. In Fig. 10, statistical storm-time day-to-day variation of the mean frequency is given for each three hour range for each station, Syowa and Memambetsu. The upper and lower frames correspond to the results at Syowa and Memambetsu, respectively. Thin dotted, thick dotted and black areas represent that the number of times of the occurrence of the emissions, whose mean frequency is in the corresponding 0.1 Hz step on the corresponding storm-time day, is less than two, three to five, and more than six, respectively. The frequency tends to become lower gradually in the course of the storm-time day. This fact will also suggest an outward shift of the plasmapause accompanying the recovery of the storm time ring current (*Dst*).

4. Long-term Variation of Occurrence of Periodic Emissions

As already mentioned in Section 3, *Dst* activity was higher in 1978 than in 1977. Nevertheless, the occurrence of the periodic emissions was rather low in that year, compared with that in 1977. This suggests that besides the development of storm-time ring current, other effects may be affecting the occurrence of the emissions. Monthly occurrences of pc 1-range pulsations observed at both Syowa and Memambetsu in the same two-year period, 1977–1978, are shown in Fig. 11. The black histo-

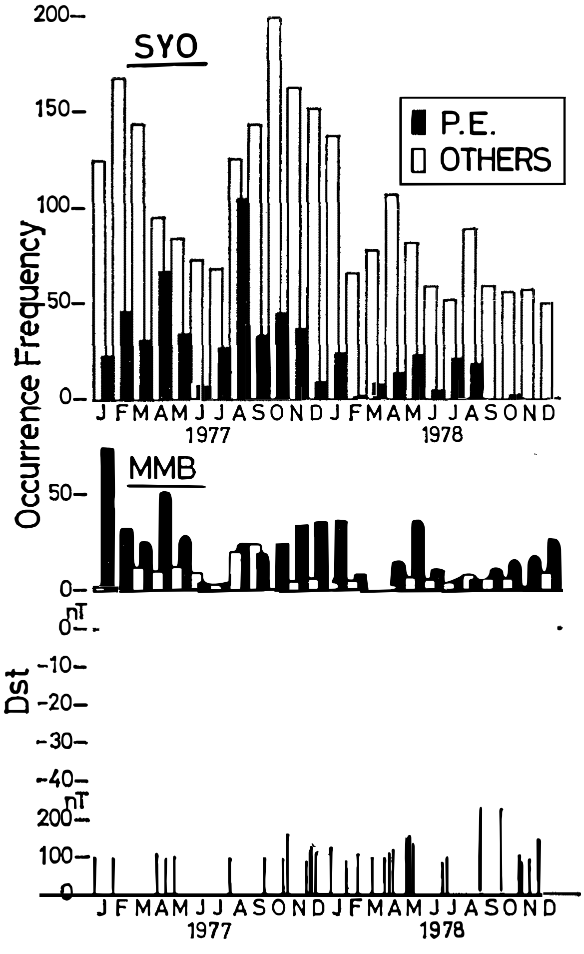

Fig. 11. *Long-term variations of pc 1 at SYO and MMB. The black histogram gives the occurrence of periodic emissions (PE). The white histogram gives the occurrence of other emissions. Monthly mean Dst index and the storm range of the horizontal component at Kakioka are given in the bottom panel.*

gram corresponds to periodic emissions. While, the white histogram corresponds to other emissions such as HM chorus. At the bottom of the figure, the monthly mean *Dst* and the maximum range of the horizontal component of individual intense storms observed at Kakioka are given. It is seen clearly that occurrences of not only the periodic emissions but also of the other pulsations decreased remarkably in 1978 compared to those in 1977. Such a long-term variation of occurrence seems to be an important factor for interpreting the observed characteristics of the emissions. These will be examined in more detail in a future paper.

5. Summary and Discussion

In the present paper, some interesting and important features of periodic emissions are investigated statistically based upon the data obtained at both auroral and low latitudes. These features are closely related to *Dst* and *Kp* magnetic activity indices. The results are summarized as follows:

(1) At both auroral and low latitudes, the emissions are observed usually during the recovery phase of an intense magnetic storm.

(2) A peak of occurrence of emissions at low latitudes appears on the second or third day after the maximum of *Dst*. The peak at auroral latitudes occurs about two days later than that at low latitudes.

(3) The equatorial *Dst* disturbance and the occurrence of the emissions at low and auroral latitudes are closely related. When the *Dst* develops sharply, the emissions are observed usually only at low latitudes. When the *Dst* development is gradual and not so large, the emissions are apt to appear rather at high latitudes.

(4) The mean frequency of periodic emissions observed at low latitudes is rather higher than that at auroral latitudes.

(5) At both low and auroral latitudes, the mean frequency shows a clear diurnal variation especially during a magnetically disturbed condition.

(6) The mean frequency usually becomes higher for higher *Kp* activity. That is, for a disturbed period with $Kp \geqq 3-$, the frequency is usually higher than in a quiet period.

It might be concluded from such *Dst* dependence that the emissions are generated by an ion cyclotron resonance in the recovery phase of an intense magnetic storm near the plasmapause. Such a conclusion has been already obtained by similar analysis in the previous paper (KAWAMURA *et al.*, 1981). The time lag of the occurrence peaks between low and auroral latitudes suggests an outward shift of the source region, the plasmapause, during the recovery of *Dst*. Because the plasmapause will shift to higher latitudes with decreasing *Kp* activity and the path of propagation from the plasmapause latitudes to low latitudes becomes longer. Therefore, the emissions will be subjected to more intense attenuation during the propagation through the ionospheric duct.

Ion cyclotron resonance frequency, f_r, is proportional to $B^2 Ni^{-1/2} v^{-1}$, where B and Ni are magnetic field intensity and magnetospheric ion (proton) density, respectively. Provided that not only B but also Ni is roughly in inverse proportion to the cube of the geocentric distance, the resonance frequency will decrease significantly with the outward shift of the plasmapause. Therefore, it can be deduced that the *Kp* dependence of the mean frequency of the emissions indicates that the above shift is related to the *Kp* activity. Moreover, both the difference of the mean frequency between low and auroral latitudes and the diurnal variation of the frequency especially in disturbed conditions will reflect the size and the configuration, such as the dawn-dusk asymmetry, of the plasmapause. In a quiet condition the plasmapause will be not yet subjected to contraction, however in a disturbed condition the plasmapause is significantly compressed and the so-called dawn-dusk asymmetry results from magnetospheric convection driven by the solar wind.

In any case, it will be concluded from the above various facts that the source region of the periodic hydromagnetic emissions is near the plasmapause and the generation mechanism of the emissions can be explained by an ion cyclotron resonance caused by storm-time ring current protons. The conclusions are illustrated schematically in Fig. 12. A similar figure has been shown already in a previous paper (*e.g.* KUWASHIMA *et al.*, 1981). In the pre-storm stage, the storm-time ring current (*Dst*) has not yet developed and plasmasphere is not yet subjected to contraction. At this stage, such periodic emissions will be not generated. Once a large magnetic storm

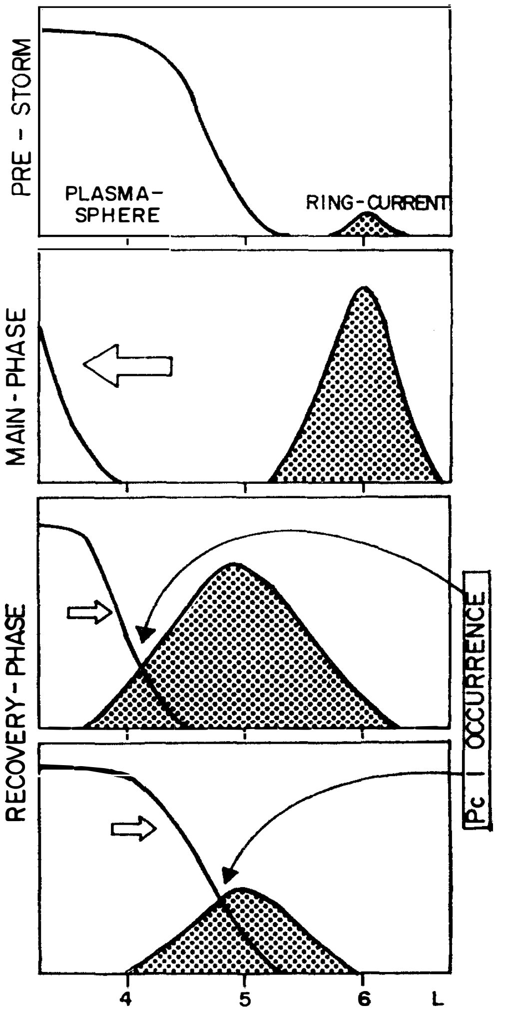

Fig. 12. A proposed model which shows the generation mechanism of periodic emissions in the magnetosphere.

occurs the plasmapause will be intensely compressed. Throughout the storm main phase, the compression will continue. The wave-particle interaction caused near the plasmapause by the ring current protons does not yet occur at this stage. Then, the compressed plasmapause returns gradually with the lapse of storm-time and on the second or third day after the maximum development of the *Dst*, the periodic emissions are generated by the above interaction near the plasmapause which is still at the inner *L*-shell. At this stage, therefore, the emissions are observed mainly at lower latitudes and the mean frequency is rather high. The plasmapause, the source region of the emissions, will continue to shift outwards throughout the recovery phase of the storm. Therefore, the observed region of the emissions also shifts to higher latitudes with the lapse of time and so that the mean frequency becomes lower. Both the time lag of the occurrences between low and auroral latitudes and the diurnal variation of mean frequency in the disturbed condition are consistent as the source region is near the plasmapause in the storm recovery phase and shifts outwards in association with the progress of the storm.

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