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CHARACTERISTICS OF SUBSTORM-ASSOCIATED VLF/ELF EMISSIONS AT MEDIUM LATITUDES

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Abstract: Substorm characteristics of VLF emissions are studied and we show that substorm-associated VLF emissions are an important and useful tool for investigating only the wave-particle interaction process, but also the particle injection process during substorms. Special effects in VLF emissions with drifting center frequency are found to take place predominantly in the two local time sectors; dawn (LT~06) and premidnight (LT=20–24 h). First, the characteristics of dawnside VLF emissions associated with substorms will be reviewed based on our previous work. As a very interesting property, the substorm-associated VLF/ELF emissions on the dawnside exhibit a rise in their central frequency with local time. We have presented its interpretation in terms of the energy dispersion of the electrons drifting from the midnight particle injection region toward the generation region (LT~06). A few events of substorm-associated VLF hiss in the premidnight with a peculiar frequency drift were first discovered from our European VLF campaign and their characteristics are presented. The generation of hiss emissions just inside the plasmapause is interpreted due to a quasi-linear cyclotron instability of the electrons injected from the plasma sheet. A new type of frequency drift in VLF hiss in the premidnight sector discussed here is such that the central frequency sharply increases first and followed by a gradual decrease during two successive substorms. This frequency drift is reasonably accounted for by a model combining an L-shell drift of energetic electrons injected during the first substorm and a subsequent decrease under a large-scale convection electric field during the development of the event. The later decrease in frequency may be related to an additional injection of particles due to the development of the second sunstorm. Finally, we will suggest future experimental work to be carried out to examine the validity of our proposed models.

1. Substorm Aspects of VLF/ELF Emissions in Medium and Subauroral Latitudes

Among different types of VLF/ELF emissions observed on the ground as well as within the magnetosphere, those which are associated with magnetic disturbances attracted particular attention of researchers (HAYASHI and KOKUBUN, 1971; RYCROFT, 1972; BULLOUGH *et al.*, 1974; KAISER and BULLOUGH, 1975; PARADY *et al.*, 1975; FOSTER *et al.*, 1976; HAYAKAWA *et al.*, 1977, 1981, 1984). The excitation of these waves can be reasonably attributed to the injection of plasma sheet electrons into the inner magnetosphere, so that the study of substorm aspects of VLF/ELF emissions makes it possible to investigate the corresponding wave-particle interaction process, the injection and drift process of particles during substorms, the magnetospheric plasma structure and so forth. Our analysis in this paper will concern one of the most important types of those emissions, known as medium- and subauroral-latitude VLF/ELF emissions.

In order to make the extensive study of mid-latitude VLF/ELF emissions, we carried out the VLF campaign in Europe (Brorfelde (L=3.0) and Chambon-la-Foret (L=2.0)) during the three winters from 1976 to 1979. The preliminary results from the last year's campaign were described in HAYAKAWA *et al.* (1981), and their initial result has indicated that the occurrence of mid-latitude VLF emissions tends to be concentrated predominantly to the two local times, dawn and premidnight. In Section 2 the characteristics peculiar to the dawnside VLF/ELF emissions in close association with substorms are first dealt with. Then, we present newly discovered properties of the substorm-associated VLF emissions in the premidnight sector, and the interpretation for the characteristic frequency drift of premidnight VLF emissions is given in Section 3. Finally, Section 4 summarizes the conclusion and future experiments to be carried out.

2. Substorm-Associated VLF/ELF Emissions in the Dawn Sector and Their Frequency Drifts

An interesting phenomenon concerned with the VLF/ELF emissions in the subauroral and medium latitudes, being clearly associated with substorms, is that they exhibit a regular frequency drift in the dawn sector. Figure 1 is a typical example of such a drift in the average frequency of VLF emissions with local time, which is observed probably outside the plasmapause and this is reproduced from CARPENTER *et al.* (1975). The figure shows that the VLF/ELF emissions of the order of 30-min duration and with rising center frequency occurred following successive substorm intensifications indicated by arrows. This kind of frequency drift in the dawn sector has been reported in several earlier publications (VERSHININ, 1970; CARPENTER *et al.*, 1975; VERSHININ *et al.*, 1979; PARK *et al.*, 1981; SMIRNOVA, 1984; HAYAKAWA *et al.*, 1986). Some papers of these are concerned with the discrete emissions (such as chorus) (CARPENTER *et al.*, 1975; PARK *et al.*, 1981; SMIRNOVA, 1984), while other papers are concerned with the hiss emissions (VERSHININ, 1970; VERSHININ *et al.*, 1979; HAYAKAWA *et al.*, 1986). However, the nature or mechanism of these

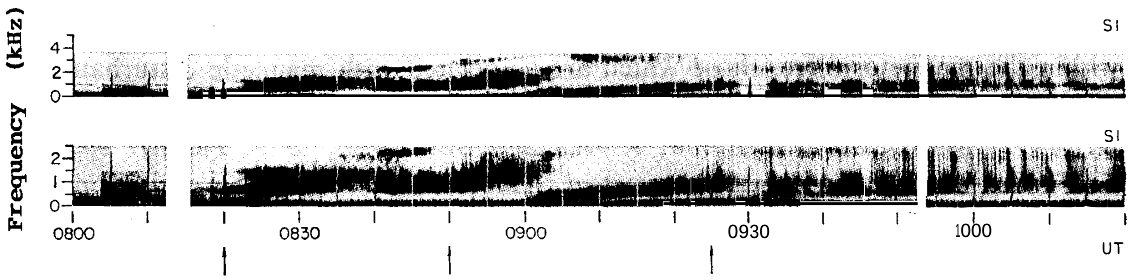

Fig. 1. The frequency increases of subauroral VLF emissions (chorus) in dawn sector which are closely associated with successive substorm intensifications (from CARPENTER *et al., 1975). The upper and lower panels show the Siple (L~4.0) record in the 0–5 kHz and 0–2.5 kHz range. Arrows indicate the times of substorm intensifications. 08 UT=03 LT.*

frequency drifts and their association with substorms remained essentially unclarified. Recently HAYAKAWA *et al.* (1986) gave the first quantitative estimation of frequency drift based on the detailed examination of six events selected from their VLF campaign data (November 1978 to February 1979). One typical example of the mid-latitude VLF hiss associated with a substorm is illustrated in Fig. 2. Figure 2(a) indicates the temporal variation of the geomagnetic activity during the period from

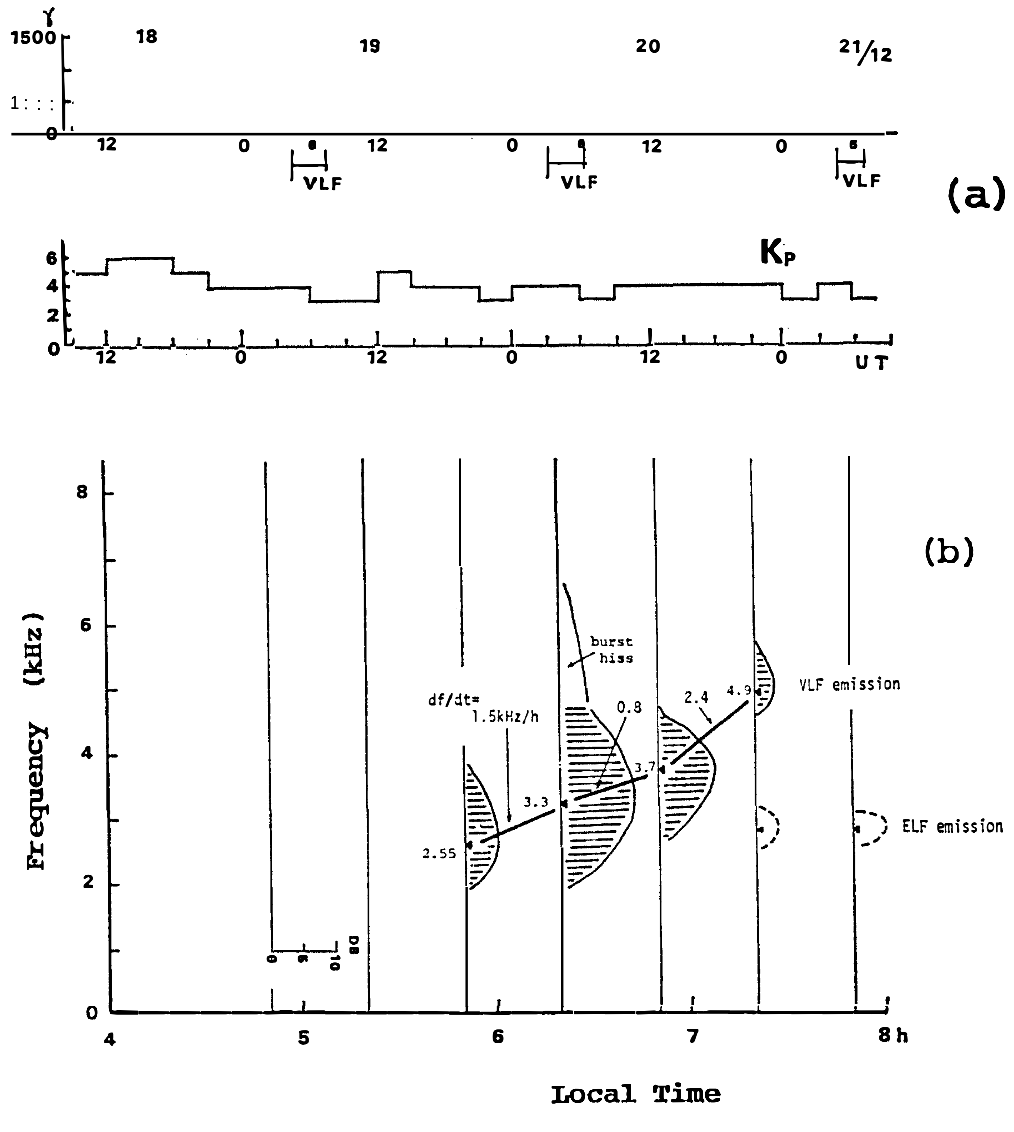

Fig. 2. (a) The temporal variation of the geomagnetic activity from 18th to 21st December, 1978. The upper panel refers to AE index, and the lower K_p *index. The times of occurrence of VLF emissions are indicated below the abscissa of the AE index. (b) The local time dependence of the frequency of VLF/ELF emissions at Brorfelde for the event of 21st December, 1978. The VLF emissions exhibiting a regular frequency drift are indicated by a shaded part. The ELF emissions, which are not the subject of this paper, are indicated by a white part with broken line envelope. The frequency of the maximum intensity for each band is also indicated by a triangle, with its frequency value. The curve roughly connecting the triangles for VLF emissions gives the frequency increasing phenomenon, and the drift rate is estimated.*

18th to 21st December, 1978 and the periods when we observed VLF emissions are indicated. Among the three events of VLF emissions, the event of 21st December, 1978 is illustrated in Fig. 2(b). The figure presents the temporal evolution of the frequency of emissions observed at Brorfelde. The frequency interval where the intensity exceeds the prescribed threshold is indicated as a shaded part and the intensity is expressed in a logarithmic (dB) scale. A frequency of the maximum intensity is indicated by a triangle and its numerical value is also given in dB. As seen from the figure, the observed emissions are composed of two bands; VLF band approximately above 3 kHz and ELF band below 3 kHz. Since the ELF band is very stable, we can distinguish easily those VLF emissions from ELF emissions. We find that the VLF emissions show a regular frequency drift. The frequency increases with a drift rate (df/dt) of 0.8–2.5 kHz/h with local time in this case. The duration of the hiss events is about 1.5 hours as seen in the figure, which is much longer than that of chorus event near the plasmapause discussed by CARPENTER *et al.* (1975). This is reasonably interpreted in the following way. We can find that the hiss is generated just inside the plasmapause, while CARPENTER *et al.* (1975) have indicated that the chorus is excited outside the plasmapause. Then we expect a distinct difference in the resonant energy of electrons responsible for generating the hiss and chorus, which results in the difference in the emission durations. The important characteristics of substorm-associated VLF hiss for all the events including the event in Fig. 2, are summarized as follows. (1) The emissions observed at Brorfelde consist of two bands, ELF ($f \lesssim 3$ kHz) and VLF ($f \gtrsim 3$kHz). The VLF emissions are identified as being of the hiss type. (2) The VLF emissions are observed during the decreasing phase in geomagnetic activity as indicated by K_p index, but in a close association with substorms as indicated by the peaks of AE index. The peaks of AE index which seem to be related with the emission generation, preceded the beginning of the emissions by 6–11 hours. The emission occurrences are highly concentrated in the LT sector just around 6 h. (3) The ionospheric exit region of the emissions has been determined by the direction findings, which has yielded that the emissions are widely distributed in the ionosphere in a latitude range from the plasmapause to a lower L shell, but the region of the maximum intensity is likely to be close to the inner boundary of the plasmapause. (4) The observed emissions exhibit a regular frequency increase. The rate of frequency increase has a tendency to decrease at later LT's, in most cases. The maximum rate was as much as 2.5 kHz/h. HAYAKAWA *et al.* (1986) have shown that the features (1), (2) and (3) can be understood with a quasi-linear model of cyclotron instability of the electrons injected in association with substorm activities. Then, they have made the first attempt to estimate quantitatively the df/dt based on the energy dispersion of electrons drifting eastward from the midnight sector of their initial injection toward the generation region of VLF emissions (dawn sector), and they have obtained a conclusion that the theoretical df/dt is in good agreement with the observed rate, which supports the validity of their model.

However, further observational work is required to show the definite evidence for our proposed model. For example, the direction finding over a wide frequency band (OHTA *et al.*, 1987) at a few stations in the subauroral and medium latitudes, would be of great use in tracing the displacement of emission generation region with frequency. Even if we do not use the wide-band direction finding, it may become possible to use an array of VLF receivers spaced in longitude to indicate the occurrence and subsequent drift and decay of particle clouds. Additional information on the interrelationship of VLF noise bands with electric fields and particle events would be invaluable.

3. Substorm-Associated Mid-Latitude VLF Emissions in the Premidnight Sector and Their Frequency Drifts

As mentioned in Section 1, we observe many VLF emissions in the premidnight sector. After a close inspection of many VLF events obtained during their same campaign, HAYAKAWA *et al.* (1988) have found out a new and interesting phenomenon of frequency drift in VLF emissions in the premidnight, being clearly associated with the magnetospheric substorm activity. This kind of frequency drift in premidnight VLF emissions associated with substorms, has not been reported insofar as we know, and some of its fundamental and important properties will be described in the following. We have found two clear events of this kind, and the better example (7th January, 1979) of them will be described. Figure 3(a) illustrates the temporal evolution of the geomagnetic activity during the event; AE index (upper panel) and 3 h K_p index (lower panel). The interval in which VLF emissions were observed, is indicated by |—| in the upper panel, and the time of maximum VLF intensity by a

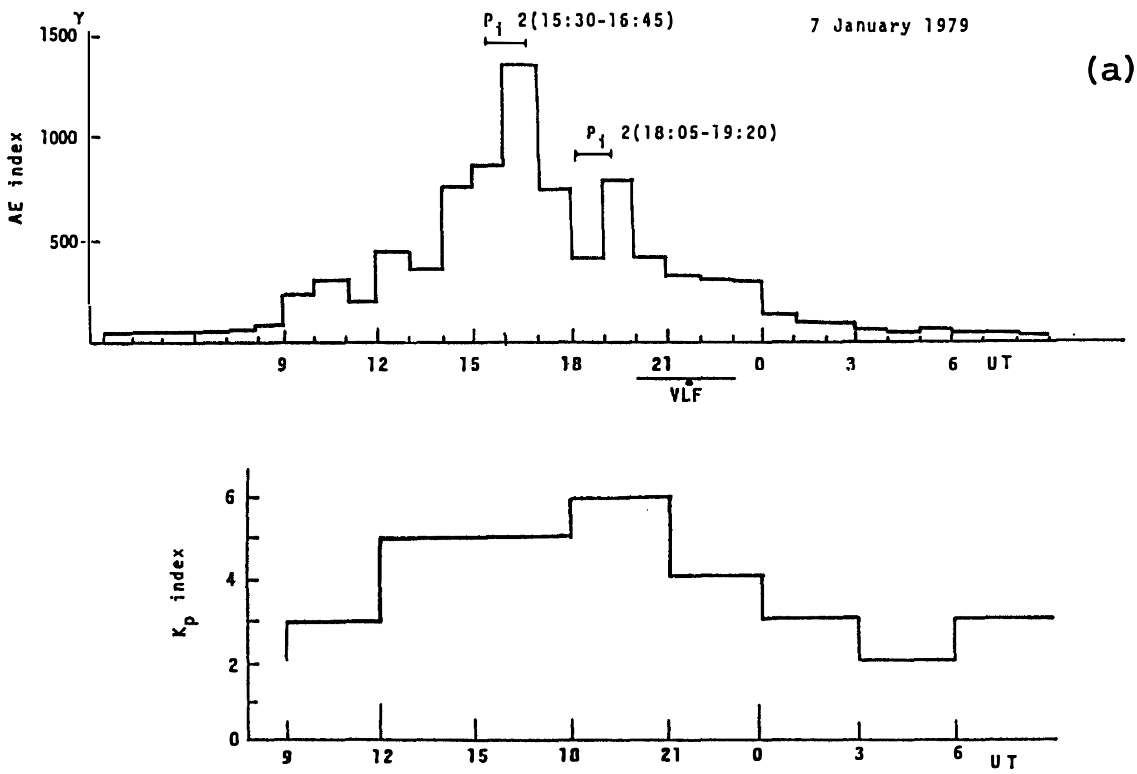

Fig. 3 (a)

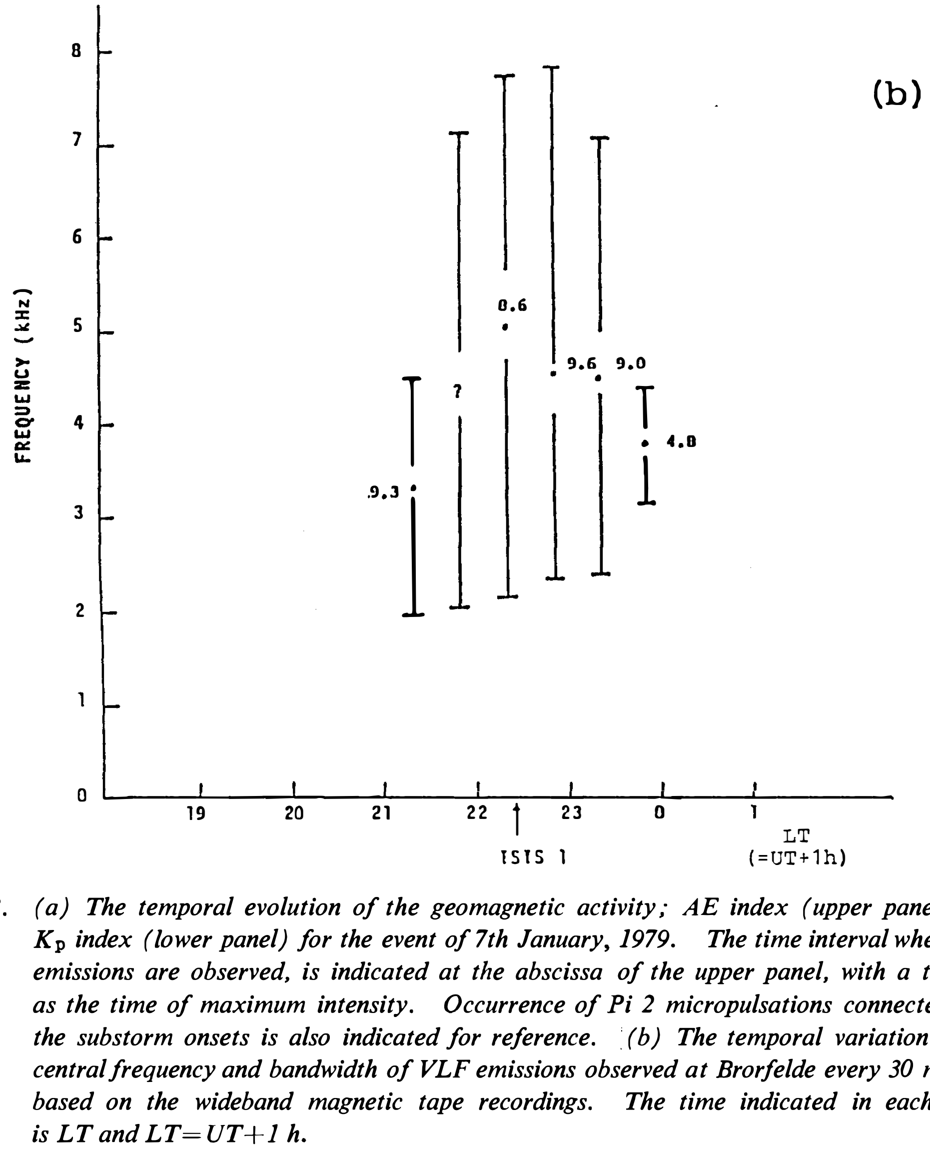

Fig. 3. *(a) The temporal evolution of the geomagnetic activity; AE index (upper panel) and K_p index (lower panel) for the event of 7th January, 1979. The time interval when VLF emissions are observed, is indicated at the abscissa of the upper panel, with a triangle as the time of maximum intensity. Occurrence of Pi 2 micropulsations connected with the substorm onsets is also indicated for reference. (b) The temporal variation of the central frequency and bandwidth of VLF emissions observed at Brorfelde every 30 minutes based on the wideband magnetic tape recordings. The time indicated in each panel is LT and LT= UT+1 h.*

triangle. It seems that these VLF emissions can be related with substorms as indicated by the preceding peaks in the *AE* index variation. Furthermore, the occurrence of two successive substorms is confirmed by the observation of Pi 2 micropulsations which are believed as a manifestation of substorm onset. The time delay of the beginning of VLF emission intensification behind the major peak in the *AE* index is about 5 hours. Figure 3(b) indicates the temporal evolution of the central frequency and bandwidth of VLF emissions observed at Brorfelde every 30 minutes. As seen from the spectra of VLF emissions at some particular times (LT=2220 and 2250) in Fig. 4, they are clearly of the hiss-type, and the temporal evolution of VLF emission frequency exhibits a specific variation such as an inverted V shape as seen in Fig. 3(b). The lower cutoff frequency increases slightly with LT, but not so much. On the other hand, the upper cutoff frequency is found to show a sharp increase followed by a gradual decrease.

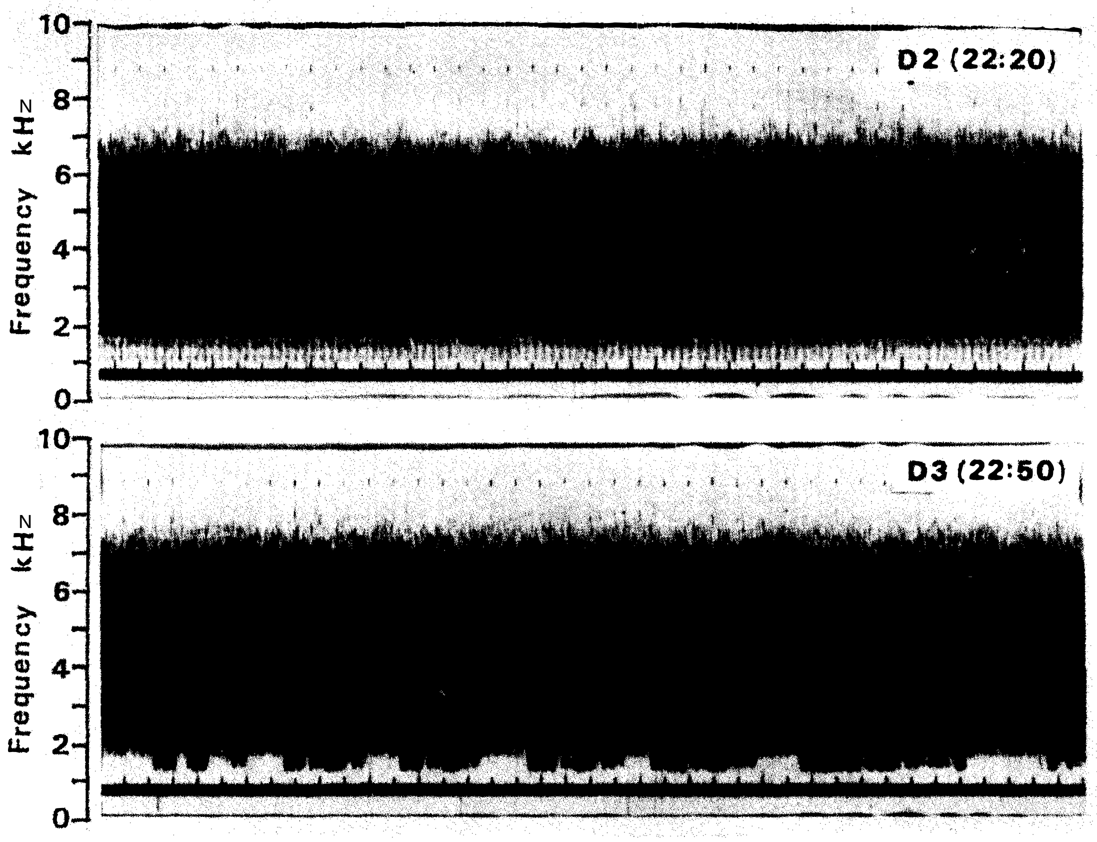

Fig. 4. The dynamic spectra of VLF emissions at LT=2220 and 2250 in the premidnight sector on 7th January, 1979.

At the time indicated by an arrow below the abscissa in Fig. 3(b), the simultaneous ISIS satellite VLF record is available. This satellite orbit during 2124–2130 UT as indicated by * in Fig. 5, was very close to our ground stations of Brorfelde and Chambon-la-Foret. So we compare the *in-situ* VLF measurement in the topside ionosphere (see Fig. 6) with the ground-based VLF hiss described above. During the time interval until 2126:15 UT (L=4.05), there were completely no emissions. Very active VLF emissions took place in the time interval from 2126:15 to 2128:25 UT (L=4.05 to 2.6), and the VLF spectra were composed of two bands. The high frequency band was impulsive emissions above 5 kHz, so-called polar VLF hiss, with the lower cutoff frequency fluctuating irregularly with time. The other component in ELF frequency band exhibited a sharp low frequency cutoff at ~1.5 kHz and a certain variation in the upper cutoff frequency. The maximum in the upper cutoff (f~5 kHz) was observed at 27 min 20–30 s (L~3.2). Thereafter, the ELF component seems to have decreased in its intensity and quenched just before the encounter with the plasmapause (28 min 25 s, L~2.6) which is inferred from the appearance of whistlers (Tixier *et al.*, 1984). When the satellite entered the plasmasphere, we had a drastic change in VLF spectrum. Just before the plasmapause crossing (*i.e.*, 2128:25 UT), the noise observed in a band from 1.5 kHz to 4.0 kHz, seems to be a leakage of VLF hiss existing within the plasmasphere. Inside the plasmasphere, we have a steady band-limited VLF hiss. Its lower cutoff frequency was constant

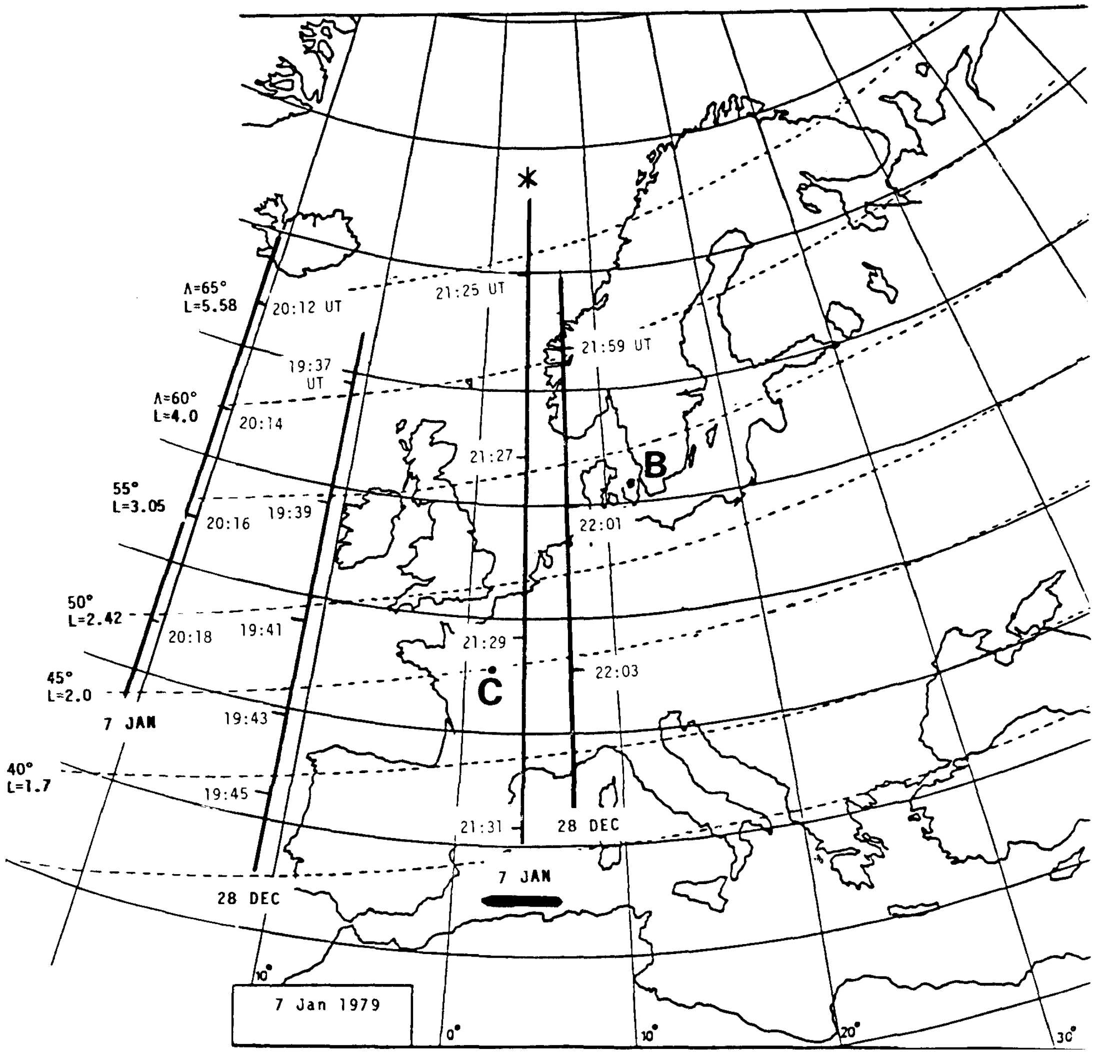

*Fig. 5. The trajectory of the ISIS satellite orbits for the event of 7th January, 1979; * indicates the orbit for which the in-situ VLF measurement is available.*

at 1.5 kHz over a wide L range. There are some uncertainties in the precise estimation of the upper cutoff frequency due to the rotation of the antenna, as it is modulated. However, we find that it is 4.0–5.0 kHz just inside the plasmapause and increases up to ~7.0 kHz or above at 2129:00 UT (L~2.30). The VLF spectrum at this time is found to be exactly the same in the frequency range and structure as that at 2120 UT on the ground in Fig. 3(b). This strongly suggests that the ground-observed VLF hiss at 2120 UT (2220 LT) is related with VLF emissions observed on the satellite within the plasmasphere.

Important features of the substorm-associated VLF emissions occurring in the premidnight sector have been summarized, including the characteristics of the events in Fig. 3; (1) The VLF emission activity preceded the development of two successive substorms. (2) The emissions observed were of the hiss-type and are excited mainly within the plasmapause. (3) The emission frequency increased sharply initially and was followed by a subsequent gradual decrease. Although the detailed descrip-

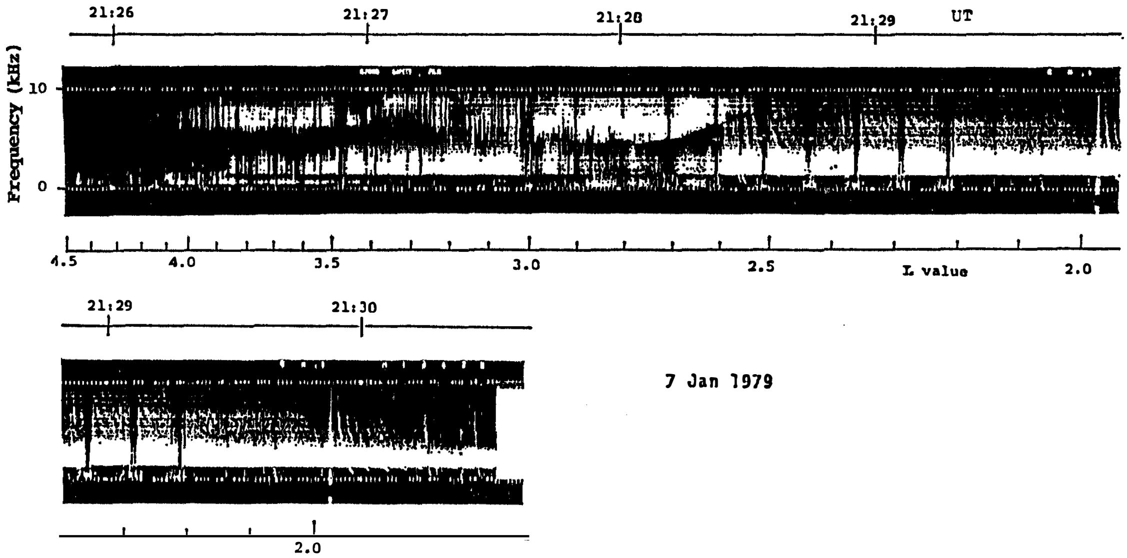

Fig. 6. The VLF wideband spectrum from the ISIS satellite from 2126–2130 UT on 7th January, 1979. The altitude is in a range from 700 km to 580 km. In the figure, black and white are reversed, so that a very white part indicates strong emissions.

tion of the phenomena and the interpretation will be presented elsewhere (HAYAKAWA *et al.*, 1988), we will briefly mention our essential points in the following. The problems of the temporal evolution of the wave spectrum are interpreted in terms of a quasi-linear electron cyclotron model for wave excitation, as in the case of dawnside VLF emissions.

The mechanism of frequency drift is discussed below. The frequency corresponding to maximum intensity of the waves can be estimated as (HAYAKAWA *et al.*, 1986)

$$\omega_{max} = \frac{c^2 \Omega_{eq}^3}{q w_{//}^2 \Pi_{eq}^2} \tag{1}$$

where Π_{eq} and Ω_{eq} are the electron plasma frequency and gyrofrequency in the equatorial magnetosphere in the excitation region. c is the speed of light, $w_{//}$ is the characteristic parallel thermal velocity of incoming electrons, q is the coefficient depending on the anisotropy of incoming electrons as well as the distribution of electron density. This equation has been derived under the assumption that the distribution of incoming electrons with respect to the modulus of their velocity is Maxwellian, which seems to be not always satisfied actually in the magnetosphere. However, taking into account the roughness of the model, it seems possible to use eq.(1) even when this distribution is not Maxwellian, $w_{//}$ being the characteristic parallel velocity of incoming electrons (not obligatorily a thermal one). Equation(1) can be rewritten in a more convenient form.

$$f_{max}(\mathrm{kHz}) = \frac{1.6\times 10^9}{L^9 n_e(\mathrm{cm}^{-3})\, W_{//}(\mathrm{keV})} \tag{2}$$

where n_e is the electron density, $W_{//}$ is the parallel energy of incoming electrons and $f_{max} = \omega_{max}/2\pi$.

Each of the parameters L, n_e and $W_{//}$ on the right-hand side of eq.(2) can change during the development of the events, so as to result in a corresponding change of f_{max}. The rate of this change can be estimated from the formula as follows.

$$\frac{df_{max}}{dt}=f_{max}\left[-\frac{q}{L}\frac{dL}{dt}-\frac{1}{n_e}\frac{dn_e}{dt}-\frac{1}{W_{//}}\frac{dW_{//}}{dt}\right] \tag{3}$$

Before comparing the prediction of eq.(3) with experimentally observed values of df_{max}/dt we would like to comment on the choice of the parameters L, n_e and $W_{//}$. One can expect that the waves excited in the vicinity of the plasmapause are most easily propagated to the ground level (INAN and BELL, 1977), and our direction finding results indicated that the waves in the premidnight sector are generated just around the plasmapause. So, we take $L=2.6$ as the plasmapause location for the event discussed in this paper. The value of n_e is assumed to be constant and equal to 5×10^3 cm^{-3} because our analysis of whistlers observed at Brorfelde yielded that n_e remains roughly constant within the event.

We now discuss the third parameter on which the value of f_{max} depends, *i.e.*, characteristic parallel electron energy $W_{//}$. In order to estimate it, we must first recall some properties of energetic electron trajectories in the equatorial plane in the premidnight sector. If the electron trajectory lies far away from the Earth in the evening-morning direction: $x_0>1.76\mathscr{L}$ (x_0 is the initial position in the dawn-dusk direction at infinite distance from the Earth toward nightside direction) and $\mathscr{L}=(\mu a/|eE|)^{1.4}$ (μ is the electron magnetic moment $\mu=W_\perp/B$ (B is the Earth's magnetic field induction)), a is the magnetic moment of the Earth, e is the electron charge, and E is the value of a large-scale electric field (ALFVÉN and FÄLTHAMMAR, 1963), then the influence of the inhomogeneity of the Earth's magnetic field is small and electrons drift from the nightside to dayside magnetosphere without encircling the Earth. When $x_0<1.76\mathscr{L}$, then electrons change the direction of their drift at $1800<\mathrm{LT}<2400$ and encircle the Earth without approaching its center closer than $1.32\mathscr{L}$ at LT=1800 and $r_0\sim\mathscr{L}$ at LT=2400. Three typical electron trajectories are schematically presented in Fig. 7. Assuming $r_0=L_0 r_e$ (r_e is Earth's radius) and $\mu=W_\perp L_0^3 r_e^3/a$ and taking into account the definition of $\mathscr{L}$, we have

$$L_0=W_\perp/r_e|eE| \tag{4}$$

Remembering that the value of E changes from 10^{-4} V/m during quiet conditions to 10^{-3} V/m during disturbed conditions (PUDOVKIN *et al.*, 1977) we can see from eq.(4) that L_0 can change from $L_{0d}=W_\perp$(keV)/6.4 to $L_{0q}=W_\perp$ (keV)/0.64 (where the subscripts d and q mean disturbed and quiet, respectively). We apply these properties of the trajectories of the electrons with fixed energies W to a rough estimation of the trajectories of electrons distributed with respect to W, *i.e.*, the electrons having W as their characteristic energy.

Because the variation of K_p index is not so large for the event discussed here (7th January, 1979), we use the steady-state trajectories in Fig. 7. We can assume that $W_\perp$ is roughly equal to $W_{//}$. The latter value can be estimated from eq.(2) as $W_{//}$ (keV)$=59/f_{max}$ (kHz). From Fig. 3(b) we have $f_{max}=3.3$ kHz at the beginning of the event, and hence $W_{//}=18$ keV, $L_{0d}=2.8$ and $L_{0q}=28$. The value of

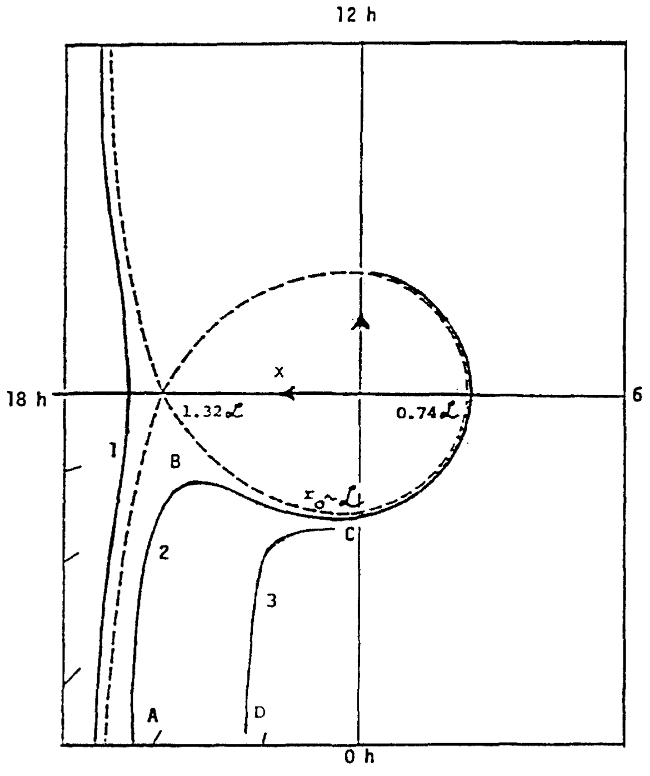

Fig. 7. A schematic illustration of the drift orbits in the equatorial plane of the magnetosphere for energetic electrons injected from the plasma sheet.

L_{0q} is much larger than 7~8 and is meaningless because the event was found to be registered during disturbed periods. We note only a small discrepancy between $L_{0d}=2.8$ and the presumed plasmapause location at $L=2.6$.

Now let us try to identify the part of electron trajectory where the waves are predominantly generated. It seems improbable that the waves described in this paper are generated when the electrons are on trajectory 1 or on the part of trajectory 2 (the role of trajectory 3 for the wave generation will be discussed later). If it would be the case, then we could expect that the electrons coming from the plasma sheet would meet the plasmapause at a certain moment, which could result in a rapid decrease of f_{max}, as predicted by eq.(2). This was not actually observed. Hence it seems reasonable to assume that the waves are excited when the electrons are on the part BC of their trajectory 2. Neglecting the influence of small deformations of this part of electron trajectory due to the influence of electric field E, we can assume that the drift time T_D of these electrons around the Earth can be evaluated by (ALFVÉN and FÄLTHAMMAR, 1963),

$$T_D(\text{hours}) \approx \frac{0.8\times 10^3}{LW(\text{keV})} \qquad (5)$$

We have assumed that the equatorial pitch angle of drifting electrons is equal to $\pi/4$, and again W is the characteristic energy of the electrons under consideration.

Equation (5) enables us to estimate the value of $\mathrm{d}W_{//}/\mathrm{d}t$ due to the velocity dispersion of drifting electrons. Let us assume that the waves are registered at one station in two subsequent local times in the premidnight sector t_a and t_b and introduce the parameters $\tilde{t}_{a,b}=t_{a,b}-18$ hours. Assuming also that the drift of electrons at different energies begins simultaneously at $t_0=1800$, and that the characteristic electron energy at $t=t_a$ is equal to W_a, we can obtain their characteristic energy W_b at $t=t_b$ from the following equation.

$$\frac{0.8\times10^3}{24L}\left(\frac{\tilde{t}_b}{W_b}-\frac{\tilde{t}_a}{W_a}\right)=\tilde{t}_b-\tilde{t}_a \tag{6}$$

and we can estimate $\mathrm{d}W_{//}/\mathrm{d}t$ as $(W_b-W_a)/2(t_b-t_a)$.

Note that when deriving eq. (6) we implicitly assumed that the group of electrons having a characteristic energy W is split into several groups, two of which have characteristic energies W_a and W_b. We also assumed that the local time of wave generation coincides with the local time of their registration. This assumption is different from that of HAYAKAWA *et al.* (1986) for which LT=0600 seems to be most favorable for their excitation when energetic electrons coming from the plasma sheet encounter the region of enhanced plasma density. No such preferable local time can be found for premidnight emissions.

The size of the forbidden zone (see Fig. 7) decreases from $\sim1.32\ \mathscr{L}$ to $\sim0.74\ \mathscr{L}$ when LT changes from 1800 to 0600 (ALFVÉN and FÄLTHAMMAR, 1963). Assuming L to be close to $\mathscr{L}$, we can roughly put

$$\frac{1}{L}\frac{\mathrm{d}L}{\mathrm{d}t}=\frac{-0.58}{12}=-0.048\ (\mathrm{h}^{-1})\,. \tag{7}$$

For the first half of the event discussed in this paper we can put $\tilde{t}_a=0318$, $\tilde{t}_b=0418$, $W_a=2W_{//}=36$ keV ($L=2.6$) and obtain, from eq. (6), $W_b=25.3$ keV, $\mathrm{d}W_{//}/\mathrm{d}t=-5.4$ keV/h. Substituting these values of the parameters with $W_{//}=W_{a//}$ and eq. (7) into eq. (3), we obtain $\mathrm{d}f_{max}/\mathrm{d}t=2.5$ kHz/h. Such a theoretical value is close to but slightly larger than our experimental data, $\mathrm{d}f_{max}/\mathrm{d}t=1.7$ kHz/h. We can presumably explain this discrepancy by a possibility that the equatorial plasmapause is located at larger L shells than that measured by ISIS. Actually, the ground-based direction finding yielded an L value of the enhanced wave intensity slightly smaller than 3.0. This possibility would also enable us to concert the value of $L_{0d}=2.8$ with the location of the plasmapause in the equatorial plane.

When looking for an alternative model which could explain the frequency increase in the second event of 28th December, 1978 (not discussed in this paper), we can note that the event is preceded by a significant decrease of K_p from 5 to 2 which is inevitably accompanied by the corresponding decrease of $|E|$. This point is discussed in more details in HAYAKAWA *et al.* (1988).

We now discuss a tentative mechanism of the observed gradual frequency decrease during the later phase of the both events. In the event of 7th January, 1979 $\mathrm{d}f_{max}/\mathrm{d}t\cong-0.5$k Hz/h, and in the second event (28th December, 1978) the value is much smaller. These rates are apparently negligibly small compared with the sharp increase rates in the beginning stages of events. We can note that the event treated in this paper begins $\sim$5 hours after the beginning of the first Pi 2 and ends $\sim$5 hours after the beginning of the second Pi 2. Hence we can expect that the conditions of wave excitation at the beginning of the event and at its end are roughly very similar, which is confirmed by a rough similarity between wave spectra in the beginning and in the end of the event. Plasma sheet electrons which are injected into the inner magnetosphere during the second substorm can follow trajectory 2 (see Fig. 7) as it was in the case of the first substorm. However, electrons following this trajectory would reach the midnight meridian after a time much longer than 5 hours and can be disregarded in our consideration. At the same time, if we consider the electrons following the trajectory located much closer to the midnight meridian (say, trajectory 3 in Fig. 7), then we can expect that the transit time of these electrons on the part DC of trajectory 3 is roughly equal to that on the part AB of trajectory 2, *i.e.*, approximately 5 hours. Thus we can expect that the electrons coming to point B from point A following trajectory 2 during the development of the first substorm excite roughly the same waves as the electrons coming to point C from point D following trajectory 3 during the development of the second substorm. In contrast to the previously injected electrons following trajectory ABC, freshly injected electrons following trajectory DC have higher energies, which, according to eq. (2), tend to reduce the frequency of excited waves. Moreover, these waves tend to be generated at slightly larger L shells, so as to result in an additional decrease of wave frequency. When the freshly injected electrons begin to dominate, we can expect a decrease of emission frequency, which is actually observed. A similar interpretation is also suitable for the observed frequency decrease during the second event.

In order to have more support to our model, it is of great use to carry out a wide-band direction finding (OHTA *et al.*, 1987) at some stations at the subauroral and medium latitudes to know the frequency dependence of the source region of VLF emissions. Additional information such as the electric field (which seems to play a significant role in our model) and particle measurements, would be essential, as well.

4. Conclusion and Future Work to Do

As is found from our present study on substorm aspects of VLF emissions, substorm-associated VLF emissions can be an important and useful tool for studying not only the wave-particle interaction process, but also the related magnetospheric phenomena such as the particle injection into the magnetosphere and magnetospheric structure during substorms. Several reports on the frequency drifts of substorm-associated morning VLF emissions have been published, but the validity of our model needs to be confirmed with sophisticated and coordinated experiments. On the contrary, new and convincing evidence of the frequency drift of substorm-associated VLF emissions in the premidnight sector has been presented and a model for this phenomenon is firstly presented in this paper. Much future experimental work should be carried out, including wide-band direction finding measurements at several stations at the subauroral and medium latitudes, and these will provide us with a definite judgement to our model.

The frequency drifts very similar to those of VLF emissions discussed in this paper, are known to exist in the ULF (Pc 1 micropulsation) region; IPDP's (intervals of pulsations with diminishing period) which are normally observed in the dusk sector in close association with substorms and are characterized by their increase in frequency with time (FUKUNISHI, 1984). Recently, this type of IPDP is also found in the morning sector and called "morning IPDP" (FUKUNISHI, 1984). The Pc 1 micropulsations are considered to be the counterpart of VLF emissions. Hence, the simultaneous study of VLF emissions with drifting frequency and IPDP's would be of great importance in clarifying the whole view of the injection and drift of particles (electrons and protons) during the substorm development, the associated wave generation (VLF and ULF waves) and the magnetospheric plasma structure (the relative position of emission generation with respect to the plasmapause), and this kind of study will be highly desirable in the near future.

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