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THE GENERATION MECHANISM OF ELF HISS IN DETACHED PLASMA REGIONS OF THE MAGNETOSPHERE, AS BASED ON THE DIRECTION FINDING RESULTS

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Abstract: This paper aims at summarizing the previous results on wave normal directions of ELF hiss emissions in detached plasma regions of the magnetosphere, observed in the equatorial and off-equatorial regions of the magnetosphere and also at the ionospheric altitudes. These direction finding results, together with the associated morphological characteristics, are utilized to discuss the generation and propagation mechanism of detached plasma ELF hiss. It is found that all of the characteristics can be interpreted satisfactorily in terms of the quasi-linear cyclotron instability by energetic electrons with energy of a few to a few tens of keV.

1. Introduction

ELF hiss is known to be most commonly observed within the plasmasphere and it is called, "plasmaspheric ELF hiss" (RUSSELL *et al.*, 1969; THORNE *et al.*, 1973; HAYAKAWA and TANAKA, 1977; HAYAKAWA *et al.*, 1985). However, there is another distinct zone for ELF emissions; detached plasma regions of the magnetosphere. Detached plasma regions are defined as regions outside the plasmapause where the cold plasma density is considerably enhanced compared with the ambient density (CHAPPELL, 1972). They are believed to originate in the plasmasphere and to be torn off either by the convection electric field (CHAPPELL, 1974; BARFIELD *et al.*, 1975) or as a consequence of the interchange instability (LEMAIRE, 1975). Several investigators (CHAN, 1974; CHAN *et al.*, 1974; CHAN and HOLZER, 1976; KIVELSON, 1976; CORNILLEAU-WEHRLIN *et al.*, 1978; HAYAKAWA *et al.*, 1986) have reported that ELF hiss emissions occur in such detached plasma regions, and we refer hereafter to those emissions as "DP hiss".

The information concerning the wave normal directions and wave distribution function in both the equatorial and off-equatorial regions is of essential importance in studying the generation and propagation mechanisms of any kinds of magnetospheric VLF emissions. CHAN (1974) and CHAN and HOLZER (1976) have investigated the wave normals of DP hiss mainly in the off-equatorial region, but due to the off-equatorial observation they were unable to distinguish between the effects of generation and propagation. HAYAKAWA *et al.* (1986) have recently determined the wave normal directions of DP hiss in the equatorial plane of the magnetosphere which is considered to be the source region.

The purpose of the present paper is to review firstly the above-mentioned direction finding (DF) studies for DP hiss carried out in the equatorial and off-equatorial regions of the magnetosphere and then to give a summary of those DF results, which will be a basis for the subsequent theoretical considerations. The comparison of the DF data at the equatorial and off-equatorial regions will allow us to distinguish the effects coming from the generation and the propagation. Recent results on the wave normal behaviors of DP hiss at the ionospheric altitude (BEGHIN *et al.*, 1985) have also been reviewed. Finally, the generation and propagation mechanisms are discussed by making full use of the overall view of the DF results in the magnetosphere and in the ionosphere.

2. Wave Normal Directions of DP Hiss

2.1. DF results in the equatorial region of the magnetosphere

Morphological properties of DP hiss in the equatorial region, such as the association of DP hiss with the plasma density enhancement, have already been discussed by CORNILLEAU-WEHRLIN *et al.* (1978). However, the DF has been made only very recently. HAYAKAWA *et al.* (1986) were the first who have determined the wave normals and wave distribution functions of DP hiss observed by GEOS 2 satellite ($L\sim6.6$) in the equatorial plane of the magnetosphere. In their work, three different DF methods have been extensively utilized; (1) MEANS' (1972) method based on the hypothesis of a single plane wave, (2) maximum likelihood method of determining the propagation directions of a few plane waves (BUCHALET and LEFEUVRE, 1981; HAYAKAWA *et al.*, 1984), and (3) maximum entropy method of determining the wave distribution (WDF) (LEFEUVRE *et al.*, 1981, 1982). The comparison of the results obtained by these three methods enables us to obtain reliable information on the wave normal directions and wave distribution functions. The DF has been made at two slightly different times and several frequencies have been analyzed for each time. Their experimental results have been summarized as follows, including important morphological characteristics.

(1) A detached plasma region detected in the equatorial region at $L=6.6$ by GEOS 2 is found to have occurred during the recovery phase of a substorm and in the LT sector of $\sim$20 h, and it is highly correlated with the presence of ELF hiss.

(2) The frequency of maximum intensity of DP hiss lies between 100 and 200 Hz as seen from Fig. 1, which is considerably lower than the corresponding frequency of plasmaspheric ELF hiss. The peak spectral power density is $\sim10^{-5}\,\gamma^2/\mathrm{Hz}$, and the half-power bandwidth is about 150 Hz. These spectral characteristics of the DP hiss seem to be in accordance with those of the DP hiss summarized in Section 2.2.

(3) The used three DF results for each event have yielded nearly the same propagation directions and so we will discuss only the results deduced from the WDF's. The WDF's of DP hiss consist of a single peak and the wave normal directions θ make small angles (less than 25°) with the Earth's magnetic field, as seen from an example in Fig. 2.

(4) The WDF is approximately circular as seen from Fig. 2 as an example. The WDF may provide information about the angular width of the unstable cone within which the waves are unstable (or they are generated), and the half-width of the unstable cone is found to increase with increasing frequency.

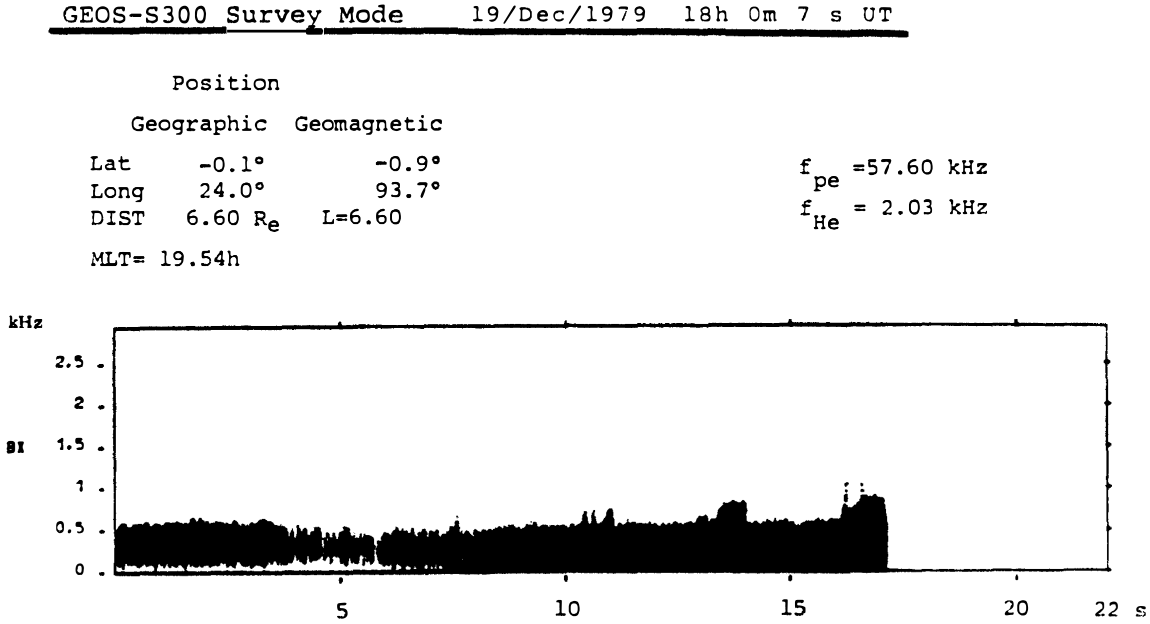

Fig. 1. An example of the frequency spectrum of ELF hiss emissions in a detached plasma region, as measured by a magnetic sensor (after HAYAKAWA *et al., 1986).*

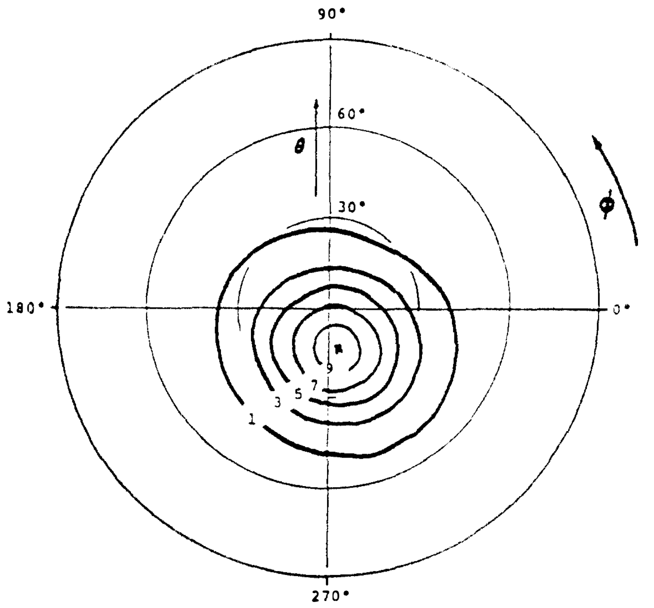

Fig. 2. Wave distribution function in the form of wave energy contour map for DP hiss in Fig. 1 at the frequency of 233 Hz (after HAYAKAWA *et al., 1986). The scale of the wave distribution function is linear and runs from 0 to 10 (corresponding to the peak and indicated by a cross). For example, 9 means the contour of the wave energy being 90% of the maximum energy indicated by the cross.*

2.2. *DF results and the associated characteristics in the off-equatorial region of the magnetosphere*

CHAN (1974) has made an extensive study of DP hiss observed mainly in the off-equatorial region of the magnetosphere, based on the OGO 5 satellite measurement, and he summarized the following important morphological features of DP hiss.

(1) For $4 \leq L \leq 12$, the center frequency of the DP hiss band falls into the range between 50 and 200 Hz with a bandwidth of about 100 Hz.

(2) All simultaneous records of ion density and DP hiss in the trough show very good confinement of the waves to the density enhancements (see Fig. 3 as an example).

(3) The wave amplitude (A) shows a direct dependence on the density (N) of detached plasma regions with a following empirical relation, $\ln(N/N_0)=KA$ for a given L value, where N_0 is the local density threshold corresponding to the threshold of wave detection and K is a constant.

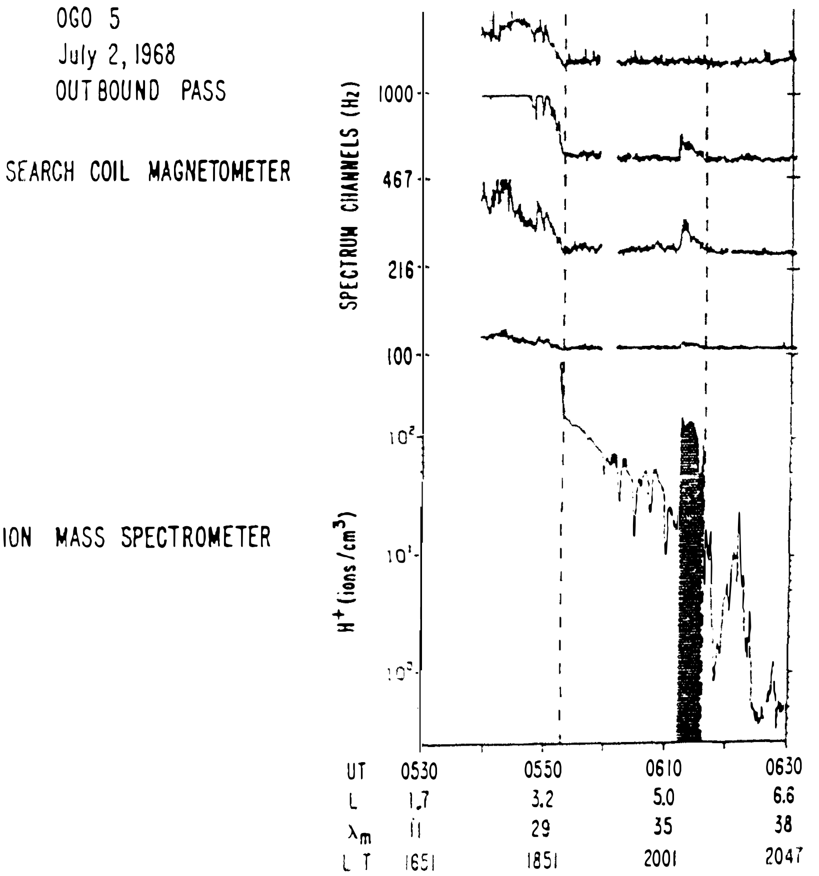

Fig. 3. Measured ion density vs. UT and simultaneously measured hiss amplitude in four spectrum channels. The region of detached plasma is shaded, and the narrow associated hiss band, seen only on two channels, correlates closely with the density enhancement (after CHAN *and* HOLZER, *1976).*

These morphological characteristics obtained in the off-equatorial region are found to be in accordance with those in the equatorial region in Section 2.1. Namely, the nature of the frequency spectra (Point (1)) is the same as Point (2) in Section 2.1. Points (2) and (3) in this section provide further quantitative support to Point (1) in Section 2.1 and the qualitative finding by CORNILLEAU-WEHRLIN *et al.* (1978) and KIVELSON (1976).

CHAN (1974) has also made an extensive study on the wave normal directions of DP hiss in the off-equatorial region, based on the triaxial search-coil observations. However, he used only MEANS' method based on the hypothesis of a single plane wave, which was only available at that time. Hence, he tried to select such events with higher coherency and higher signal to noise ratio that validate the single plane wave assumption, and his DF results are worthwhile to cite below.

(4) The wave normals show considerable scatter over an angular range, but they make less than 35° with the Earth's magnetic field. Furthermore the observation showed no latitudinal dependence of the wave normal direction (see Table 1).

Table 1. The wave normal directions of DP hiss (after CHAN, 1974).

Orbit No.	Date	UT	Geomagnetic latitude $\lvert\lambda_m\rvert$	$\cos^{-1}(\mathbf{k}\cdot\mathbf{B})$		Coherency
				Small	Large	
47	7/02/68	0612:05	35.7°	22.9°	38.0°	0.85
55	7/23/68	0126:00	42.6°	18.7°	34.8°	0.88
58	8/02/68	0816:00	1.4°	11.9°	21.2°	0.88
75	9/13/68	0243:00	35.9°	13.9°	17.5°	0.89
76	9/15/68	1630:00	42.2°	17.2°	40.7°	0.84
79	9/23/68	1310:00	34.5°	13.9°	40.8°	0.85
132	2/10/69	1823:00	6.0°	6.5°	14.3°	0.97

2.3. *DF results at the ionospheric heights*

The Aureol 3 satellite has carried out a high-resolution density measurement and a direction finding of ELF waves (BEGHIN *et al.*, 1985), and Fig. 4 illustrates an example

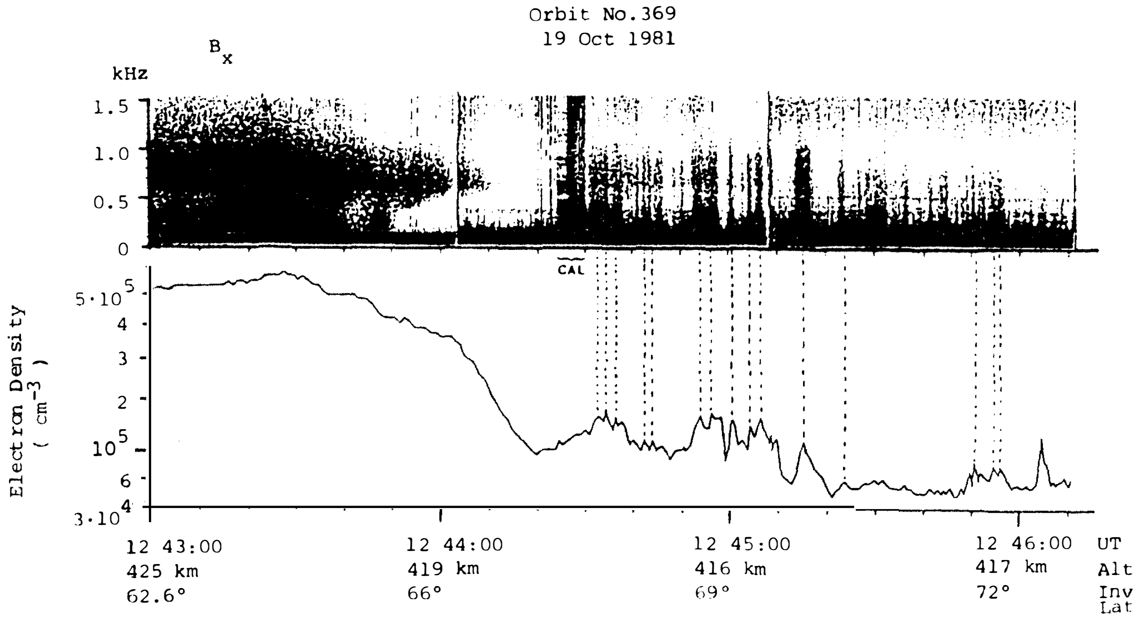

Fig. 4. An example of the correlation between ELF hiss and electron density variations (after BEGHIN et al., 1985).

of the good correlation between an enhancement of ELF hiss and high-latitude plasma ducts corresponding to detached plasma regions. Figure 5 shows another example of electron density structures correlated with the amplitude variations of the five field components in the ELF frequency range. In this figure the overall horizontal distance covered by the satellite is ~90 km at the altitude of 680 km and the invariant latitude is ~70°N. We can identify six well-defined density structures with duration of 0.6 to 1.6 s (indicated by shaded regions) with peak to peak density variation in a range from 5 to 29%. BEGHIN *et al.* (1985) have indicated that the wave amplitude variation cannot be accounted for either by the variation of wave admittance or by the local wave growth, and they have checked whether the observed wave power fluxes associated with crests of ionization can be explained by the ducting theory. A crucial factor

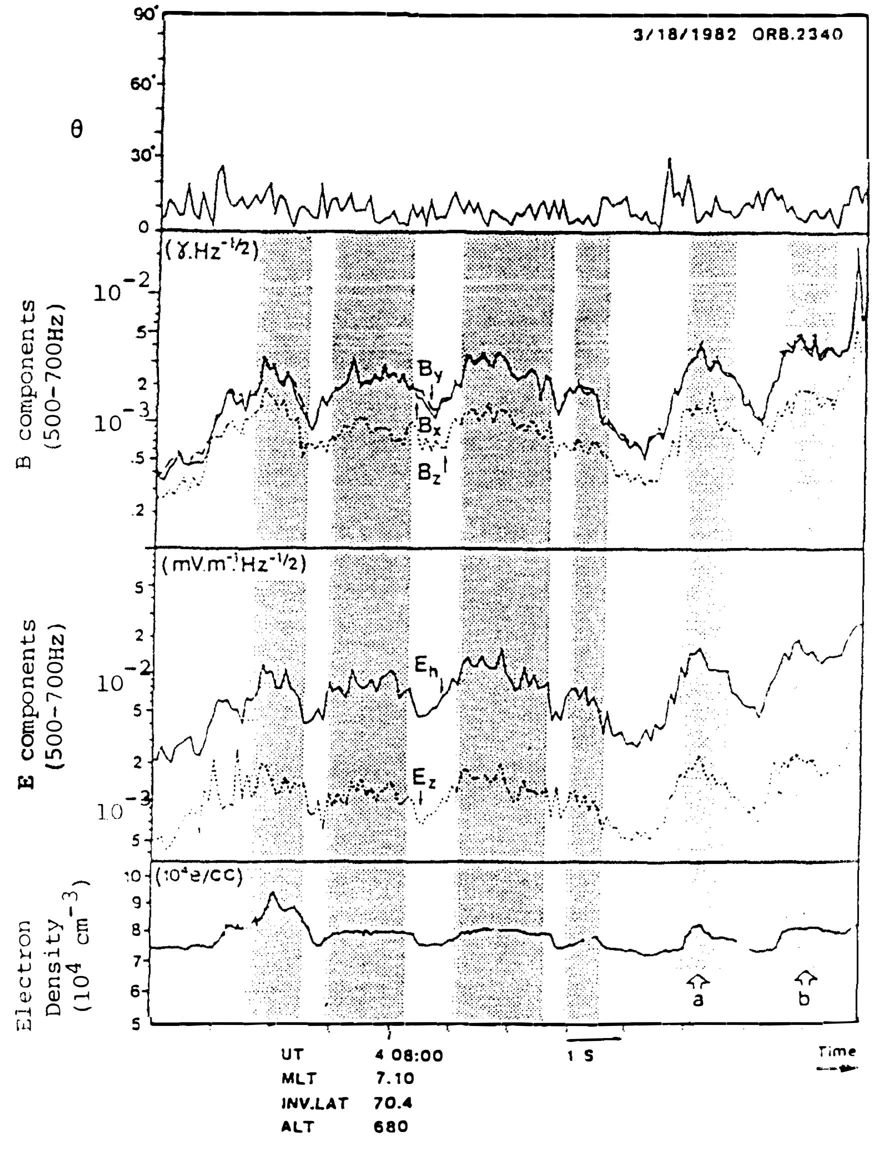

Fig. 5. Correlation between the amplitude variations of the five components of ELF hiss and the electron density variation. Top panel represents the time evolution of the wave normal angle with respect to the Earth's magnetic field (after BEGHIN *et al., 1985).*

in favour of such a ducting is that the waves have propagated nearly along the magnetic field (θ less than 30°) as seen from the top panel of Fig. 5. They have used MEANS' method for the determination of wave normal directions, because the consideration on the degree of wave polarization etc. has validated a single plane wave assumption of MEANS' method.

3. The Generation Mechanism of DP Hiss

The information obtained on the wave normal directions of the DP hiss is of great importance in studying its generation and propagation mechanisms. The observations in Section 2.1 were made exactly in the equatorial plane, which is considered to be the mostly likely source region for the emissions (HELLIWELL, 1967; RUSSELL *et al.*, 1969; TSURUTANI and SMITH, 1977). The hypothesis of local generation at the equator seems to be supported by the experimental fact (Point (4) in Section 2.1) that the WDF's are almost circular, even though the peak is slightly shifted away from the origin. If the relevant waves had propagated over some distances from the source in the non-ducted mode, the distribution in azimuth would be concentrated into the magnetic meridian plane (THORNE, 1969; CAIRO and LEFEUVRE, 1986). Furthermore, even if we assume a ducted propagation from the source and if the detached plasma region were rather elongated in longitude (*i.e.* if it had a sheetlike structure) (TAYLOR *et al.*, 1970, 1971), we would again expect a tendency for the azimuthal direction to be in the meridian plane. These expectations seem to be in contradiction with the nearly circular shapes of the WDF's. The small shift in θ from the origin (14° in Fig. 2) might have resulted from the effects of propagation over a short distance, and it is reasonable to consider that circular shapes of the WDF's reflect the properties of the source, that is, they are consistent with isotropic emission generation at the source in the sense that the emission is independent of the azimuthal angle around the magnetic field and depends only on the polar angle.

The DF results given in Section 2.1 (Point (3)) indicate that the wave normals make small angles (less than 25°) with the magnetic field, and we can conclude experimentally that the wave growth at the equator is strongest for the quasi-longitudinal propagation direction ($\theta \sim 0°$). This experimental finding of the maximum growth for quasi-longitudinal propagation around the equator is in good agreement with the theoretical prediction by KENNEL (1966) on electron cyclotron instability. He assumed an E^{-n} energy spectrum for hot electrons and found that the wave growth is most rapid at $\theta=0°$ at the lowest frequencies ($\Lambda \lesssim 0.3$) and furthermore that a 20° (50°) half-width for the unstable cone corresponds approximately to an $E^{-3}(E^{-2})$ spectrum for the hot electron distribution function, with the additional finding that the unstable cone widens with increasing frequency. Point (4) is Section 2.1 yields that the unstable cone half-width (defined as the range in θ angle from the peak to the edge labelled 1 in the WDF's) increases with increasing frequency such as $\sim$35° at $\Lambda=0.12$ to $\sim$50° at $\Lambda=0.15$, which is again in agreement with the theory. The half-width of the experimental unstable cone can be satisfactorily interpreted in terms of the average slope of E^{-2} for the hot electron distribution function. However, in the calculations of KENNEL (1966), he did not include cold electrons. Since the half-width of the unstable cone depends on the relative numbers of cyclotron and Landau resonant electrons, a co-existence of cold electrons with hot electrons makes the unstable cone narrower, and hence the detailed quantitative comparison with the present experiment is required to check the theory. KIVELSON (1976) has shown experimentally that there exists a lower limit in the particle flux for energetic electron distributions that are responsible for the generation of emissions.

The smallness of wave normal angles at the equator is favorable to both wave generation and ducted propagation down to the ionosphere. As seen in Section 2.2 (Point (4)), CHAN (1974) has found that the wave normal directions of DP hiss at high geomagnetic latitudes (30°–50°) show a great scatter over an angular range from 2° to 40°, but they are mostly less than 35°, which are larger than the θ values at the equator (Point (3) in Section 2.1). Furthermore, he has found no latitudinal dependence of wave normal characteristics. It is likely that the additional scatter in wave normal directions at higher latitudes may be due to the scattering of wave normals by the density irregularities during the course of ducted propagation away from the equatorial source region (HELLIWELL, 1965). The electron density enhancement is usually extremely high in the detached plasma regions (as in HAYAKAWA *et al.*, 1986 and in Fig. 3) compared with the values for normal whistler ducts as given in ANGERAMI (1970), so that the wave trapping up to larger θ values is possible, in agreement with CHAN's observational results. These DP hiss may reasonably be thought to remain trapped owing to the density enhancement of the detached plasma region down to the ionosphere. In accordance with this expectation, the wave normals of DP hiss at the ionospheric heights discussed in Section 2.3 are found to make small θ angles (less than 30°) with the magnetic field, and this supports the ducting idea.

For more quantitative studies, the quasi-linear electron cyclotron theory has been proposed, as an extension of the linear electron cyclotron instability theory. Following KENNEL (1966), papers by ROUX and SOLOMON (1971), by ETCHETO *et al.* (1973) and by SAZHIN (1984) presents self-consistent calculations, leading to estimates of the frequency and power density at the peak in the whistler spectrum. A dynamic equilibrium is established, in which the waves are being continuously generated with a persistent injection and disappearance of particles into the loss cone by pitch-angle diffusion. The stationarity of the process of wave generation is achieved by the balance between the total wave amplification along the field line and the wave loss accompanying a partial reflection of the waves from the ionosphere. In these theories, quasi-longitudinal ($\theta \sim 0°$) or ducted propagation is assumed, which is experimentally verified by the smallness of θ values obtained by the DF results in the present paper. The frequency f_{max} at which the wave energy is maximal, is given by (SAZHIN, 1984),

$$f_{\mathrm{max}} = \frac{c^2 f_{\mathrm{H}}^2}{w^2 1.2 f_{\mathrm{p}}^2}\,, \tag{1}$$

where c is the speed of light, f_{p} and f_{H} are respectively the electron plasma and gyrofrequency at the equator where the waves are excited, and w is the characteristic velocity of the incoming electrons at the L shell of the wave generation. The corresponding maximum power spectral density $\langle B_{\mathrm{f}}^2 \rangle_{\mathrm{max}}$ at f_{max} can be given by (SAZHIN, 1984).

$$\langle B_{\mathrm{f}}^2\rangle_{\max} \propto n_{\mathrm{eq}} L^{5.5} W_{\mathrm{o}}^{1.5} L_{\mathrm{o}}^{4.5} \frac{\mathrm{d}n_i}{\mathrm{d}t}\,, \tag{2}$$

where n_{eq} is the equatorial electron density on the L shell where the waves are generated, W_{o} is the electron energy at $L=L_{\mathrm{o}}$ (L_{o} can be chosen arbitrarily), and d $n_i/\mathrm{d}t$ is the rate of influx of electrons. The observed peak frequency such as summarized in Sections 2.1 and 2.2 is used together with the corresponding appropriate f_{p} and f_{H} values in eq. (1) to estimate the value of the characteristic energy of the incoming electrons corresponding to w, and we obtain the value of a few to a few tens of keV. Equation (2) implies that the peak power $\langle B_{\mathrm{f}}^2\rangle_{\max}$ is directly proportional to $n_{\mathrm{eq}}L^{5.5}$ for a given incoming particle distribution and influx rate $\mathrm{d}n_i/\mathrm{d}t$. In the case of Fig. 1, L is fixed to 6.6, so $\langle B_{\mathrm{f}}^2\rangle_{\max}$ is proportional to n_{eq}. As may be seen from Figs. 1 and 3, n_{eq} within the detached plasma region seems to be about ten times the ambient plasma density, resulting in an enhancement of DP hiss, which is consistent with the observation (Point (3) in Section 2.2).

Finally, we can conclude that all of the observed characteristics and the DF results within the magnetosphere and in the ionosphere can be interpreted satisfactorily in terms of the quasi-linear electron cyclotron instability.

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