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THE WAVE NORMAL DIRECTIONS OF CHORUS EMISSIONS IN THE OUTER MAGNETOSPHERE

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Abstract: The GEOS-1 satellite wave data have been used to determine the wave normal directions of chorus emissions in the off-equatorial region of the outer magnetosphere based on the wave distribution function method. The wave normal directions with respect to the magnetic field have been discussed as functions of wave frequency normalized by the local gyrofrequency and of the slope, df/dt of an emission. Two different kinds of chorus structures (rising tone and impulsive one) have been treated. A comparison of the present behaviour of off-equatorial wave normal directions with the previous equatorial wave normal measurements has enabled us to discuss the generation and propagation mechanism of chorus emissions with different structures (rising tone, falling tone, constant frequency tone and impulsive one), and finally we suggest the future problems to study.

1. Introduction

Chorus emissions are one of the most intense naturallysoccurring electromagnetic signals detected in the outer magnetosphere. Chorus is observed near the equatorial plane mainly outside the plasmapause and occurs during geomagnetic substorms and storms (TSURUTANI and SMITH, 1974; BURTIS and HELLIWELL, 1976; ANDERSON and MAEDA, 1977; HAYAKAWA *et al.*, 1977, 1984; GOLDSTEIN and TSURUTANI, 1984). Its generation is closely associated with hot (10–100 keV), anisotropic substorm electron clouds (ANDERSON and MAEDA, 1977; HAYAKAWA *et al.*, 1977, 1984; TSURUTANI *et al.*, 1979; ISENBERG *et al.*, 1982) and the wave and particle results seem to be consistent with wave generation by the loss cone instability (KENNEL and PETSCHEK, 1966).

Although many of the gross features of chorus and its effects such as the scattering of magnetospheric particles into the loss cone, have already been determined, the details of the wave properties and the instability generating the emission are still less well understood. Information concerning the distribution of wave normal directions of chorus is considered to be an invaluable tool for studying such wave

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properties, wave generation mechanism and mechanism of producing d*f*/d*t*. There have been very few reports on the direction finding of chorus (BURTON and HOLZER, 1974; CORNILLEAU-WEHRLIN *et al.*, 1976; HAYAKAWA *et al.*, 1984; GOLDSTEIN and TSURUTANI, 1984), and so further direction finding studies for chorus emissions will be of great importance for better understanding of the generation and propagation mechanism of chorus emissions.

The present paper deals with the direction finding results for chorus emissions in the off-equatorial region of the outer magnetosphere, on the basis of the GEOS-1 satellite data. Then, a comparison of the present result of off-equatorial wave normal behaviours with the previous equatorial observations will be made in order to discuss the generation and propagation mechanism of chorus emissions. Finally, we will suggest the future problems to study.

2. Data Source and Direction Finding Method

The field data are signals obtained by the so-called S-300 experiment on board GEOS 1 satellite which measures continuously the electric and magnetic components of the field. The observed signals are subjected to the onboard analyses; the sweep frequency analyzers (SFA's) and the correlator. Six SFA's have a bandwidth of 300 Hz and are swept in frequency in the range 0–77 kHz. Before being telemetered to the ground, the signals are transposed in frequency, passed through identical low-pass filters at 450 Hz, and sampled at 1.488 kHz. The correlator output, after suitable Fourier transformation on the ground, yields a spectrum of 2.5 kHz (ELF part of the survey mode) or 5.0 kHz (VLF part). The orbit of the satellite is given in KNOTT (1978), and the detailed description of the GEOS S-300 experiments is given in S-300 EXPERIMENTERS (1979).

Spectral matrix at each Fourier component is estimated by using only the three magnetic field components in the VLF part. Several direction finding methods have been proposed (see LEFEUVRE *et al.*, 1981, 1982, for example), but in this paper we utilize only the wave distribution function (WDF) method in which the maximum entropy concept is applied to the measured spectral matrices (LEFEUVRE *et al.*, 1981, 1982; HAYAKAWA *et al.*, 1986). The plasma parameters necessary for this WDF methods are the electron plasma and gyrofrequencies, which are simultaneously measured on board the satellite. In order to illustrate the direction finding results, we adopt a Cartesian coordinate system O_{xyz} where the z axis is parallel to the Earth's magnetic field $\vec{B}_0$, the axis O_x is in the magnetic meridian plane and is directed toward the Earth, while O_y completes the orthogonal set and is directed westward. The wave normal direction $(\vec{k})$ is characterized by the polar angle θ between $\vec{k}$ and $\vec{B}_0$ and by the azimuthal angle ϕ, the origin of which is O_x.

3. Wave Spectra and Wave Normal Directions of Chorus Emissions in the Off-Equatorial Region of the Magnetosphere

We have investigated, in details, an event with intense chorus emissions. This event was detected on 12th October, 1977 at a geomagnetic latitude λ_m of 17.4° and

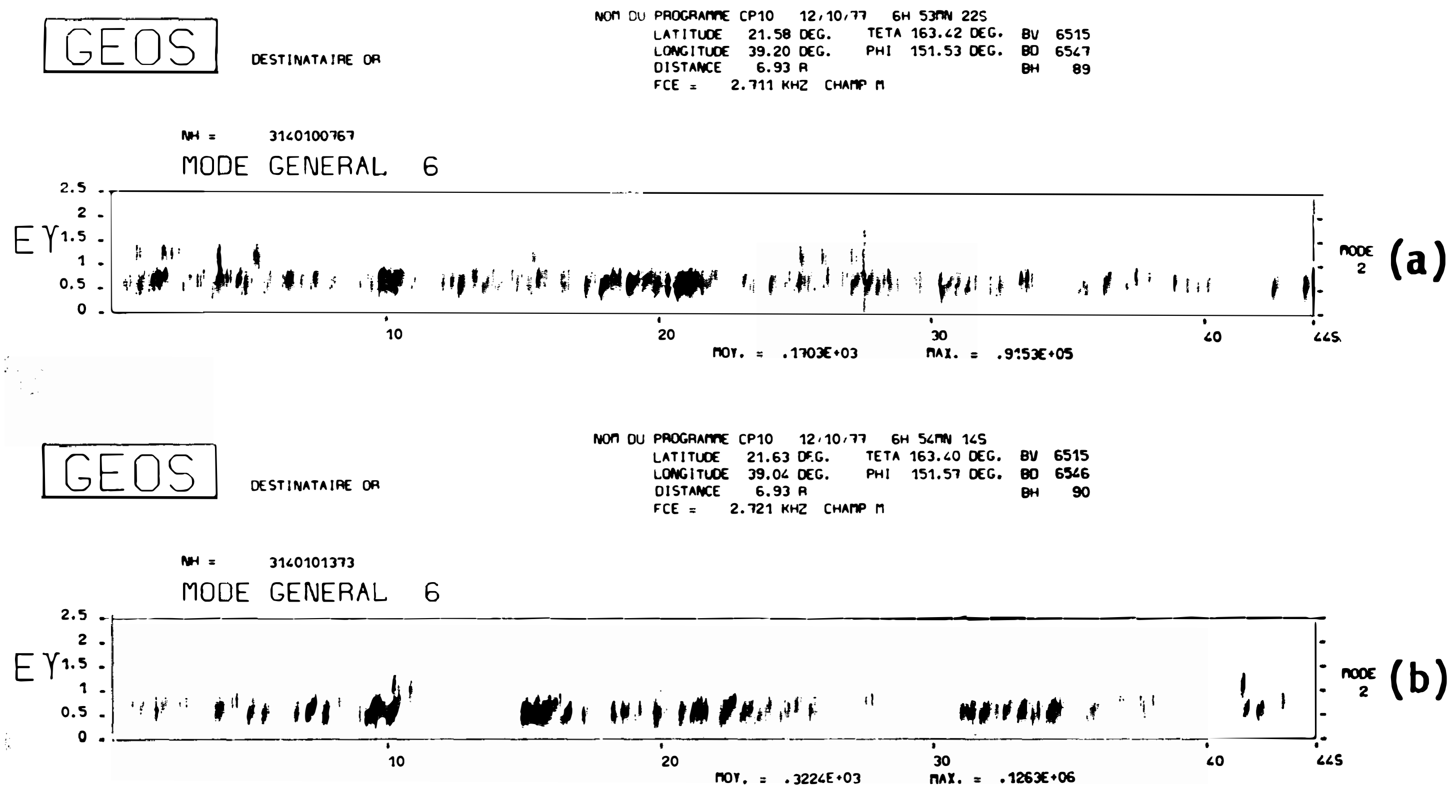

Fig. 1. 44 s ELF (0–2.5 kHz) spectrograms of chorus emissions observed by E_Y antenna on board GEOS 1 satellite on 12th October, 1977. (a) 0653:22 UT and (b) 0654:14 UT.

an L value of 7.60 and MLT$\cong$10 h. The L value of the observing position was obviously outside the plasmapause and so the relevant chorus emissions were observed outside the plasmapause. Figures 1(a) and (b) illustrate 44 s ELF spectrograms of VLF/ELF waves in a range up to 2.5 kHz at two slightly different times during this event and the figures imply a coexistence of different kinds of chorus structures with different df/dt's. On occasions, as in Figs. 1(a) and (b), the spectrum is composed of two bands being separated by a frequency gap at ~1.0 kHz. The upper-band emissions in this case are relatively weak and reveal only a few structured elements. Such upper-band emissions have been investigated in details by MUTO *et al.* (1987), who have identified them as being half-gyrofrequency VLF emissions generated near the equator. The subject of this paper is not these upper-band emissions, but the lower-band emissions in a frequency range below about 1 kHz. In all of the figures in Fig. 1, the lower-band emissions are seen to be very intense, consisting of structured elements. In Figs. 1(a) and (b) we find two kinds of chorus; one is impulsive (or burstlike) and the other is rising tone with positive df/dt. While, in Fig. 1(b) most of chorus are found to exhibit a moderate positive df/dt of the order of ~1 kHz/s. However, there were observed no chorus emissions like falling tones and constant frequency tones as found in TSURUTANI and SMITH (1974) and CORNILLEAU-WEHRLIN *et al.* (1976).

The direction finding measurements have been performed several times during about five minutes from 0652:29 to 0657:08 UT and at several different frequencies. The selection of analyzing frequencies is made as follows. We first make the digital grey-scale displays, which enable us to choose the frequencies where we can expect the strong intensity. Then, we have carried out the direction finding at least at one frequency for each chorus element, which means that a few frequencies are analyzed for few chorus elements. Successful WDF's have finally been obtained for 21 events during the above period; here the term "successful" means that the prediction and

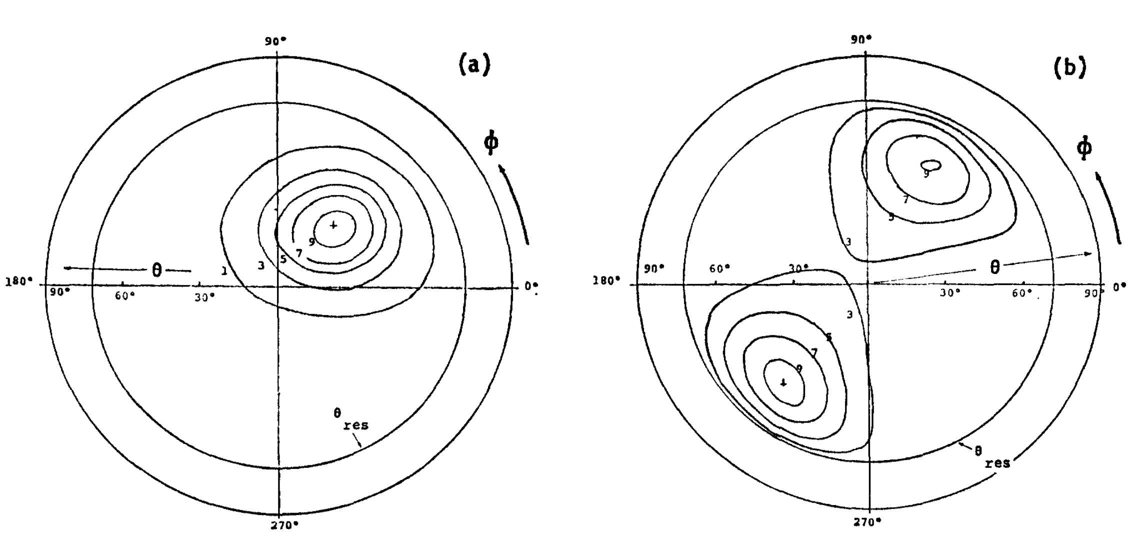

Fig. 2. Examples of wave distribution functions for chorus emissions. The scale of contours is linear and runs from 0 to 10, and the peak corresponding to 10, is indicated by +. (a) A singly peaked solution at 0655:37 230 ms UT and at 732 Hz. (b) A doubly peaked solution at 0655:36 628 ms UT and at 778 Hz.

stability parameters indicating the quality of convergence of the WDF solution (LEFEUVRE *et al.*, 1981) are satisfactory for us. Two examples of such WDF's are presented in Fig. 2. Figure 2(a) is a typical example of a singly-peaked WDF, while Fig. 2(b) corresponds to a doubly-peaked WDF. Nineteen events are found to fall in the category of a single-peaked solution as in Fig. 2(a); *i.e.* about 90% of all events analyzed. Therefore, only about 10% of the events are of the doubly-peaked WDF's as in Fig. 2(b). The (θ, ϕ) value of the peak of each WDF was estimated and the results including the analyses in Fig. 2, are summarized in Fig. 3 in the form of θ *versus* wave frequency normalized by the local electron gyrofrequency ($\Lambda = f/f_H$). For the sake of comparison, two characteristic angles of oblique resonance angle, θ_{res} and Gendrin angle, θ_g are plotted as well. In Fig. 3, we have distinguished rising tones from impulsive ones. Also, on the right, is plotted the occurrence histogram of the θ values. The corresponding occurrence histogram of ϕ is indicated in Fig. 4 for rising tones (a) and for impulsive ones (b), respectively. The normalized frequencies of the analyzed chorus events are found to lie in a range from 0.2 to 0.4. Figure 3 shows that there is no conspicuous tendency of θ value with frequency for the case of rising tones, and they take larger θ's in a range of 30°–55°. But, there seems to appear to be a tendency for waves at higher frequencies to be travelling at a larger angle to the field for impulsive chorus. Then, we can note from Fig. 4(a) for rising tones that there appears to be a concentration of the wave normals to an azimuth, ϕ=40°–50°, but there is rather a scatter in ϕ distribution for impulsive

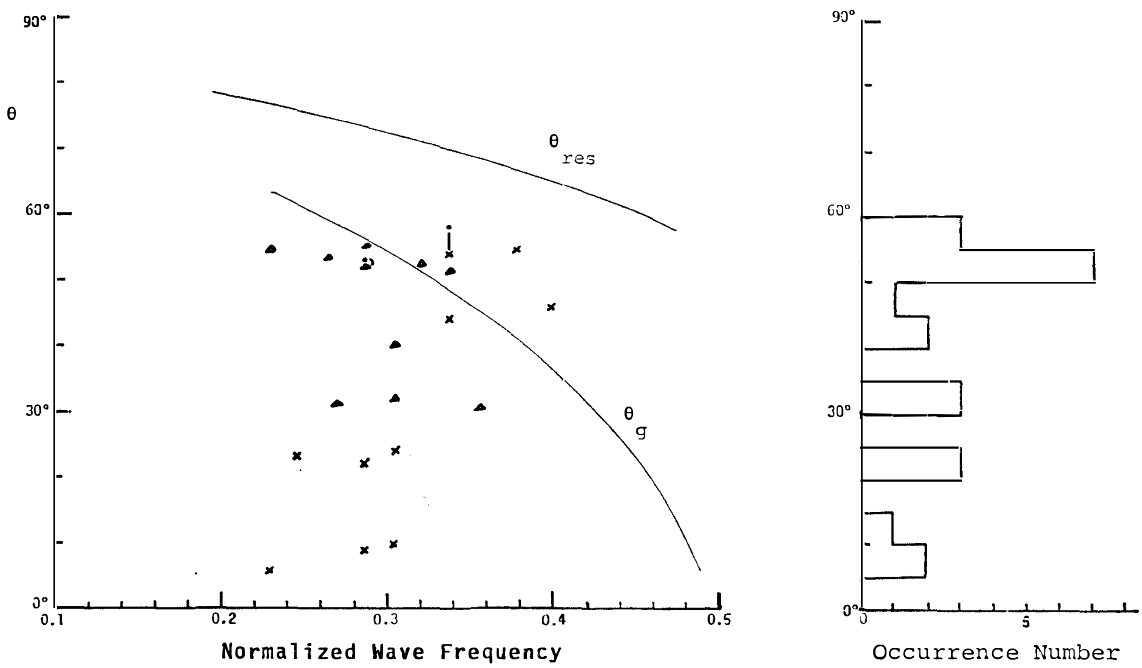

Fig. 3. Relationship between θ and wave frequency normalized by the local gyrofrequency. $\times$ refers to impulsive chorus, while $\triangle$ refers to normal rising tone chorus. For the doubly-peaked WDF, the main peak is indicated by either $\times$ or $\triangle$ and the corresponding secondary peak is indicated by a small dot connected with the main peak by a line. On the right, is plotted the occurrence histogram in θ of the events.

chorus. However, the statistical study of ϕ distribution in Fig. 4 does not seem to be so significant because of a small amount of data.

Then, the relationship between the observed df/dt of chorus and the corresponding θ value is presented in Fig. 5 for which θ is plotted as a function of df/dt. Two structures of chorus emissions are observed; *i.e.* rising tone and impulsive one. For

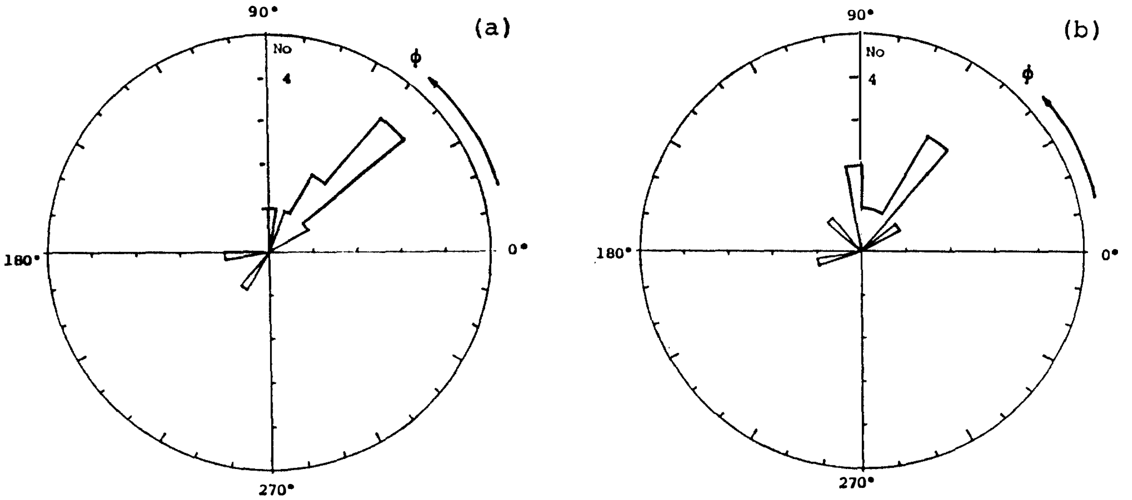

Fig. 4. The occurrence distribution in ϕ for rising tones (a) and for impulsive ones (b).

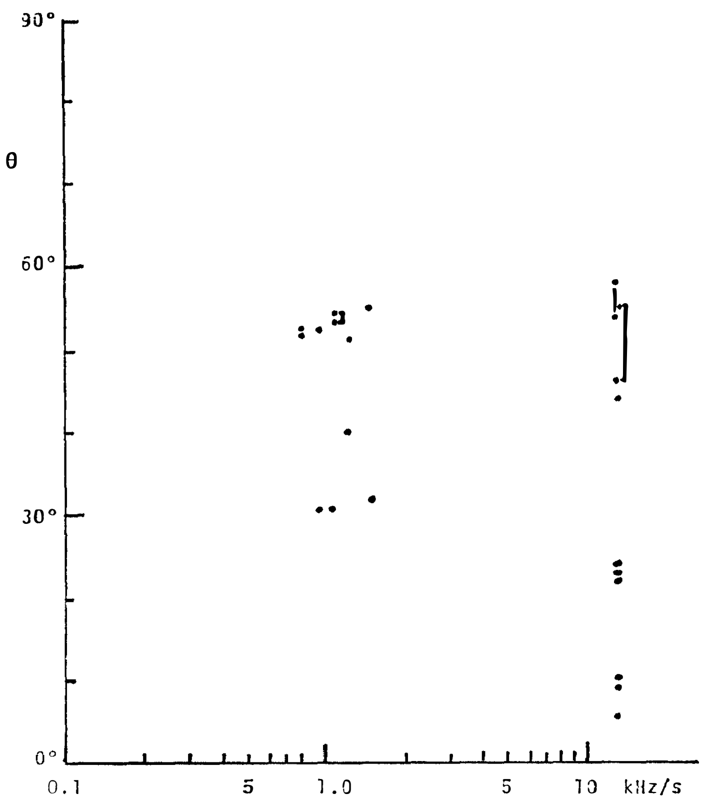

Fig. 5. Relationship between θ and df/dt. Impulsive chorus is plotted just right of $df/dt=10$ kHz/s.

the rising tones, df/dt is in a range from 0.8 to 1.5 kHz/s and the θ value is found to be in a range from 30° to 55°. While, there is a large scatter in the θ values from 5° to ~60° for the impulsive tones, but as mentioned in Fig. 3, this may be a frequency dependence of θ.

The use of three magnetic field components has yielded an ambiguity of 180° in the sense of propagation. So, we have included the E_y field in the WDF analyses in order to remove the ambiguity. However, a clear distinction in the sense determination has unfortunately not been obtained, probably due to the poor knowledge on the coupling impedance between the electric antenna and the plasma.

4. A Comparison with the Previous Equatorial Observations and the Discussion on the Generation and Propagation Mechanism of Chorus Emissions

We first review the previous results of wave normal determinations of chorus emissions made near the equatorial plane which have been made by a few investigators and whose important items have been summarized in Table 1. There are several parameters which seem to be related with the measured θ value of chorus; (1) the observing geomagnetic latitude (λ_m), (2) the normalized wave frequency (Λ) and (3) the spectral shape, or df/dt. As for the first parameter, λ_m, the observing satellites in Table 1 are located just in the vicinity of geomagnetic equator. BURTON and HOLZER (1974) have suggested that chorus (rising and falling tones) is generated at latitudes within 25° of the equatorial plane on the dayside and within 2° on the nightside. Hence, taking into account the satellite locations in Table 1, we can consider that all of their results of wave normal directions of chorus except impulsive ones should reflect the distribution of wave normal directions within the source region, although it is still possible that some propagation effects are present. Within the latitude range from 0° to 5°, GOLDSTEIN and TSURUTANI (1984) have investigated the latitude effect of θ angle of slightly falling tones and constant frequency tones, and they have found no apparent relation, implying that their result represents pri-

Table 1 Summary of the previous direction finding measurements for chorus emissions near the equatorial plane in the outer magnetosphere.

Investigators	Observing location: Geomagtic latitude (λ_m)	L value	Local time (LT)	Structure of chorus	Satellite and remarks
BURTON & HOLZER (1974)	Equator	6.0–10.0	Night (00–03h) Day (0730–1430)	Rising and falling tones	OGO 5 Observation is made at different geomagnetic latitudes (0–50°)
CORNILLEA-WEHRLIN *et al.* (1976)	2°	6.0–7.0	01h	Rising, falling tones and burst-like (impulsive)	OGO 5
GOLDSTEIN & TSURUTANI (1984)	<5°	6.0–7.0	~02h	Falling tone	OGO 5
HAYAKAWA *el at.* (1984)	0.4°	6.6	03–16h	Impulsive and rising tone	GEOS 2

marily the original distribution of wave generation directions rather than the propagation effects. As for the second parameter, the normalized frequency (Λ), GOLDSTEIN and TSURUTANI (1984) have found that larger θ's correspond to higher relative frequency, but they have described that their putative frequency dependence is open to question. This frequency dependence has also been studied by HAYAKAWA *et al.* (1984), who have indicated that there is no definite trend between θ angle and frequency. The normalized frequencies, Λ of chorus are found to lie in a range from 0.15 to 0.45 (GOLDSTEIN and TSURUTANI, 1984; HAYAKAWA *et al.*, 1984). After reviewing all of the previous works as given in Table 1, the relationship between θ value and the third parameter, df/dt is investigated now. There are reports which suggest a close association between the chorus structure and local time (LT) (BURTIS and HELLIWELL, 1976; BURTON and HOLZER, 1974; GOLDSTEIN and TSURUTANI, 1984; HAYAKAWA *et al.*, 1984). On the nightside, different kinds of chorus structures have been observed, including falling tones, constant frequency tones and normal rising tones. While, on the dayside, we observe mainly normal rising tones and also impulsive (or burstlike) ones. So, we have plotted the θ angle as a function of df/dt in Fig. 6 on the basis of the descriptions in all of the papers in Table 1. As seen from this figure, there seems to be a tendency for θ value to increase with df/dt in the region of positive df/dt. Also, when df/dt is relatively small whether it is positive (rising tone) or negative (falling tone), the θ value is relatively small such

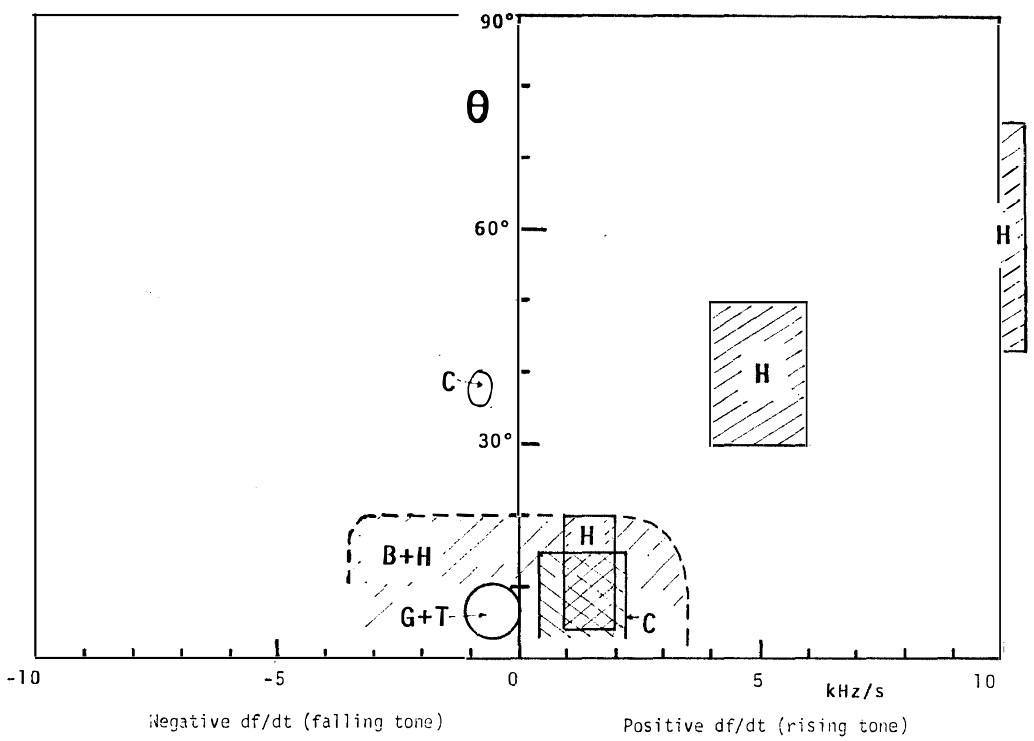

Fig. 6. Summary plot of the relationship between θ and df/dt based on the previous equatorial measurements. Again, impulsive chorus is plotted just outside of $df/dt=10$ kHz/s H means the summary from HAYAKAWA et al. (1984). G+T corresponds to GOLDSTEIN and TSURUTANI (1984), C, CORNILLEAU-WEHRLIN et al. (1976) and B+H, BURTON and HOLZER (1974).

that it is less than 30°, or rather less than 20°. On the contrary, for the region of negative d*f*/d*t* (falling tones), there does not seem to exist any definite relationship. However, it is likely that falling tones tend to exhibit larger θ values than those for small d*f*/d*t* around the origin in the figure. This putative but suggestive figure has to be confirmed by a more systematic study on many chorus events.

Now we discuss the behaviour of wave normal directions in the off-equatorial region as presented in this paper, with respect to its comparison with the equatorial observations. First, we discuss the question whether one wave or multiple waves are present in chorus. GOLDSTEIN and TSURUTANI (1984) have compared the residuals of the one- and two-direction model fits to the observed spectral matrix and they have concluded that in most cases only a single plane wave is present. As being in agreement with them, the present study based on the WDF analyses has implied that about 90% of the events are composed of a single plane wave. In the studies of BURTON and HOLZER (1974) and CORNILLEAU-WEHRLIN *et al.* (1976), they have adopted MEANS (1972) method based on the hypothesis of one direction model, but their θ values seem to be reliable because most of chorus events are due to the one-direction model even if they have erroneously determined wave normals of some chorus events if second waves were present. Within the source region near the equator, GOLDSTEIN and TSURUTANI (1984) have found that the distribution in ϕ appears to be isotropic, strongly implying that the satellite is located within the source region. Now let us compare Figs. 3 and 5. In the present paper, two different types of chorus are observed: rising tones and impulsive ones. The d*f*/d*t* of rising tones observed lies just around 1.0 kHz/s as in Fig. 5, which is apparent to be typical at these *L* values and LT's from the work of BURTIS and HELLIWELL (1976). In Fig. 6, the θ values of chorus with d*f*/d*t* of this order are found to be relatively small, less than 20° in the equatorial plane, which is likely to be an established fact. Compared with this result, Fig. 5 seems to indicate that θ's are considerably larger than those in Fig. 6 for rising tones, this being furthermore supported by the results of off-equatorial direction finding by BURTON and HOLZER (1974). Together with this, we again look at our Fig. 4. Although the amount of data is relatively small, it seems likely that there is some concentration of ϕ around a specific value for rising tones. As seen from the three-dimensional ray-tracings by CAIRO and LEFEUVRE (1986) and MUTO *et al.* (1987), the wave normal directions have a tendency to be focussed into the magnetic meridian plane during the course of propagation from the source. But, the possibility of observing emissions at a spacecraft is strongly dependent on the relative location between the source and spacecraft. Hence, we can consider that the concentration in ϕ in Fig. 4(a) implies some propagation effects having played a role, at least, for rising tone chorus observed away from the equator in this paper. So, although BURTON and HOLZER (1974) have concluded that the source region of chorus (falling and rising tones, but not impulsive) at daytime is at latitudes within 25° of the equatorial plane, it seems to us that the generation region of rising tone chorus observed at LT= 10h in this paper, is located at a latitude still lower than the satellite latitude of $\lambda_m=17°$. While, for impulsive chorus, θ value is greatly scattered in a wide range from 5° to 25° and from 45° to 60° in Fig. 5, but the θ of impulsive chorus near the equator makes large angles with the magnetic field as in Fig. 6. Because the generation mechanism of impulsive chorus is not well understood, we do not know at present, which figure at the equatorial or at the off-equatorial region might reflect the wave generation distribution at the source region.

There are many problems to be solved and we suggest the following subjects to be studied in the near future.

(1) For lower frequency (Λ=0.1–0.3) rising tones with moderate df/dt's typical at the relevant L value as studied by BURTIS and HELLIWELL (1976), their generation is due to the gyroresonance interaction between whistler-mode waves and counterstreaming electrons in the vicinity of the geomagnetic equator based on the following reasons. The first evidence is the equatorial direction finding studies (as summarized in Fig. 6). The other is the consideration of the interaction region by using the value of df/dt. HELLIWELL's (1967) theory suggests that the latitude of the interaction region is related to the slope, df/dt of an emission by the inhomogeneity of the medium. Using this theory in the relevant plasma parameters and taking df/dt=1 kHz/s, the latitude of the interaction region is found to be about 5°. So, our Fig. 5 as obtained from the off-equatorial observation at λ_m=17°, might indicate the existence of propagation effects. Ray-tracing computations will be highly required in order to confirm both the equatorial emission generation with $\theta \simeq 0°$ and the propagation effect from the equator to the spacecraft.

(2) For rising tones at higher frequencies (Λ=0.3–0.45), it is again plausible that the emissions are generated near the equator with small θ's. However, GOLDSTEIN and TSURUTANI (1984) have found a small concentration of θ's at relatively large angles just around θ_g in a frequency range, Λ= 0.3–0.45 (see Fig. 7 in GOLDSTEIN and TSURUTANI (1984)). Of course, this concentration is not so conspicuous as compared with the clear concentration of half-gyrofrequency VLF emissions at a special angle of θ_{res} (HAYAKAWA *et al.*, 1984; MUTO *et al.*, 1987). There are a few theoretical studies on this point (BRINCA, 1972; CUPERMAN and STERNLIEB, 1974) and BRINCA (1972) has predicted maximum wave growth along the field for very low frequencies, but large off-axis growth with increasing frequency. Hence, further theoretical study on which kinds of magnetospheric conditions (cold and hot plasmas) are required for oblique instability, should be done in order to explain the possibility of this off-axis wave growth at higher frequencies below $f_H/2$. The θ results in the off-equatorial region (λ_m=17°, Fig. 5 in this paper) must be considered again with the aid of ray-tracing computations as mentioned in the Item (1).

(3) More direction finding results for falling tone chorus events have to be accumulated in order to have a definite relationship between θ and df/dt if any.

(4) Impulsive chorus at the equator is found to take large θ angles as summarized in Fig. 6, but Fig. 5 suggests that there is a large scatter in θ from nearly 0° to ~60°. The structures of normal rising, falling and nearly

constant frequency tones seem to be explained in terms of the drifting oscillator model by HELLIWELL (1967). However, what is the generation mechanism of impulsive (burstlike) chorus emissions? Where are they generated and how are they propagated? Detailed study on this problem will be required.

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