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RAY-TRACING INTERPRETATION OF WAVE NORMAL DIRECTIONS OF CHORUS EMISSIONS OBSERVED IN THE OFF-EQUATORIAL REGION OF THE OUTER MAGNETOSPHERE

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Abstract: The previous direction finding measurements of chorus emissions with different spectral shapes (rising, falling, and constant tones) near the equator have indicated that those chorus emissions are generated around the equator with their wave normals being nearly aligned with the magnetic field in terms of the Cyclotron instability by energetic electrons. Their subsequent propagation in the outer magnetosphere is discussed in the present paper. First, the results of wave normal directions of chorus observed in the off-equatorial regions are reviewed; one from OGO 5 measurement and the other, our GEOS 1 result. These measurements are compared with the results of two-dimensional ray-tracing analyses for a realistic model of the outer magnetosphere. Finally, it is found that the subsequent propagation of chorus after the equatorial generation, is, on some occasions, ducted, and it is non-ducted on other occasions.

1. Introduction

Chorus is one of the most intense naturally occurring noises detected in the outer magnetosphere. Chorus is known to be observed mainly outside the plasmapause and occurs in close association with substorms and storms (*e.g.*, HAYAKAWA *et al.*, 1989 and references therein). The delay time of chorus emissions from the substorm onset has enabled TSURUTANI and SMITH (1977) and HAYAKAWA *et al.* (1986) to deduce the energy of energetic electrons responsible for chorus generation as 10–100 keV and they have suggested a loss-cone instability of substorm-injected electrons.

The instability generating the chorus emission is not completely understood from the direct and extensive wave measurements. Information on wave normal directions of chorus emissions is of greatest importance in elucidating the generation mechanism of chorus. HAYAKAWA *et al.* (1989) presented their direction finding results for chorus in the off-equatorial region of the magnetosphere, and a comparison of some previous direction finding results near the magnetic equator with those at the off-equator, has led them to conclude that chorus with normal spectral shapes are generated near the equator and it propagates toward higher latitude. However, they indicated several problems requiring further investigation, and the first one of them is an urgent need for a quantitative check on the behavior of wave normal directions far off the equator with the aid of ray-tracing computation analyses. This point is dealt with in the present paper.

2. Direction Finding Results

2.1. *Equatorial observation*

There are only a few reports on direction finding of chorus near the equator; they are briefly described here. BURTON and HOLZER (1974) determined the wave normal directions of chorus (normal rising tone) and Fig. 1 is their summary of the wave normal direction (θ) for dayside chorus at L=5–7 at different geomagnetic latitudes. Near the equator ($0° < |\lambda| < 10°$), the θ (the angle between the wave normal direction and the Earth's magnetic field $\tilde{B}_0$) is peaked at angles within 20°, such that the wave propagation is nearly aligned with the magnetic field. The definitions of λ and θ are given in Fig. 2. Then, when the observation point is located at a higher latitude, the θ value becomes considerably dispersed up to $\theta \sim 60°$. Nightside chorus is also found to have small wave normal angles. CORNILLEAU-WEHRLIN *et al.* (1976) estimated the wave normal direction of nightside chorus at L=6–7 and found that the wave normal angles of chorus with df/dt (either positive or negative) typical to these L values are small ($\theta \leqq 30°$) near the equator. Wave propagation directions of post-midnight chorus at L=6–7 are estimated by GOLDSTEIN and TSURUTANI (1984) to occur most frequently along the magnetic field. Then, HAYAKAWA *et al.* (1984) determined the wave normal directions of ordinary rising tone chorus and the wave normals of rising tones with df/dt as normally observed, are found to take very small angles (θ=5°–20°). These observations are summarized and reviewed in HAYAKAWA *et al.* (1989), and it is concluded that the wave generation seems to be maximum for purely longitudinal propagation ($\theta \sim 0°$).

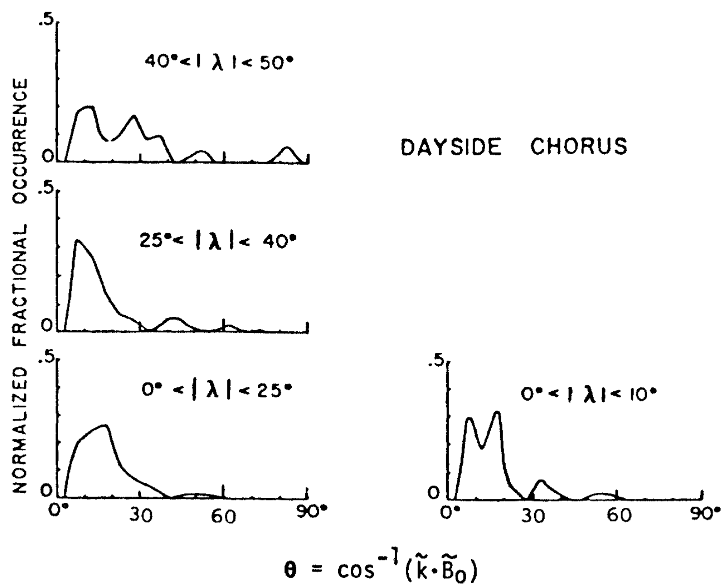

Fig. 1. The latitudinal variation of the wave normal directions (θ) of chorus emissions on the dayside (after BURTON *and* HOLZER*, 1974).*

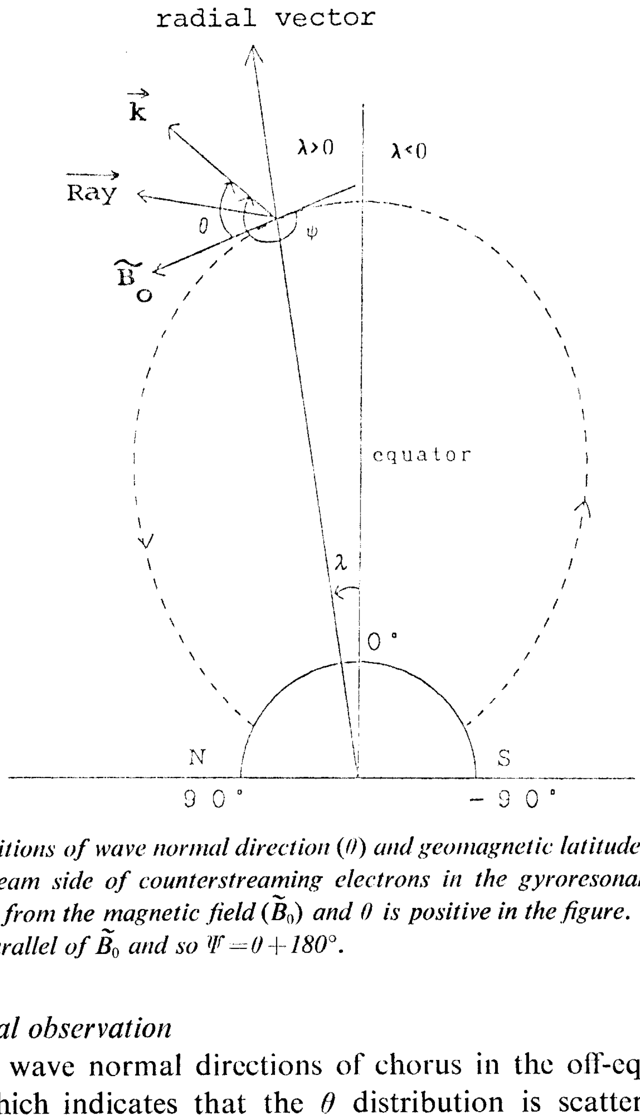

Fig. 2. The definitions of wave normal direction (θ) and geomagnetic latitude (λ). λ>0 indicates the upstream side of counterstreaming electrons in the gyroresonance. θ is measured clockwise from the magnetic field ($\tilde{B}_0$) and θ is positive in the figure. Ψ is measured from the antiparallel of $\tilde{B}_0$ and so Ψ = θ + 180°.

2.2. *Off-equatorial observation*

In Fig. 1 the wave normal directions of chorus in the off-equatorial region are also presented, which indicates that the θ distribution is scattered up to larger θ values. Figure 3 is reproduced from HAYAKAWA *et al.* (1989), which illustrates the wave normal angles for ordinary rising tone chorus emissions observed far away from the equator ($\lambda = 17.8°$) at $L = 6$–7 at LT$\simeq$10 h on board GEOS 1 satellite. In this study, the wave distribution function method (*e.g.*, MUTO *et al.*, 1987) is adopted for the direction finding, while previous other direction findings except this study and that of GOLDSTEIN and TSURUTANI (1984) are all based on MEANS' (1972) method assuming a single plane wave. A majority of cases consisted of a single peak which is indicated by a large dot in Fig. 3, while one chorus is composed of two peaks, the major peak being indicated by a large dot and a minor peak by a small dot linked with the corresponding large dot. Figure 3 indicates that the θ value at $\lambda \simeq 18°$ lies in a range from 30° to 60° in the frequency range of chorus elements. In the result of BURTON and HOLZER (1974) as in Fig. 1 in the higher latitude, the wave normals are widely distributed up to $\theta \sim 60°$, but there still exists a group whose θ is small such as less than 30°. On the contrary, the present study in Fig. 3 indicates only the large wave normal angles such as $\theta = 30°$–$60°$, and we cannot identify small θ angles as observed by BURTON and HOLZER (1974).

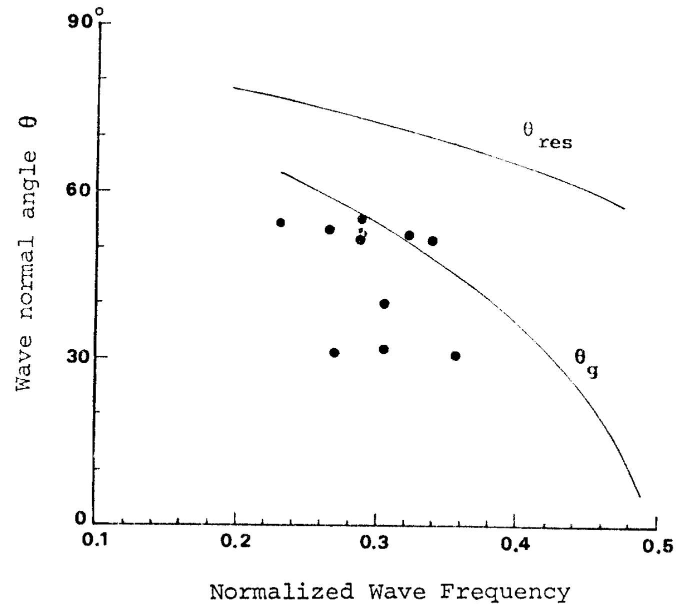

Fig. 3. The θ value of chorus emissions ($\lambda \simeq 18°$) defined from the peak intensity in the wave distribution function as a function of the wave frequency normalized by the local gyrofrequency (after HAYAKAWA *et al., 1989). When the event is characterized by a single peak, its θ value is indicated by a large dot. There is one event with two plane waves, and the major peak is indicated by the same large dot and the secondary peak is given by a small dot which is linked with the corresponding major peak.*

3. Ray-tracing Computations and Their Comparison with the Direction Finding Results in the Off-equatorial Region

Two-dimensional ray-tracing computations have been performed for a magnetospheric model in order to check quantitatively the previous wave normal measurements. The dipole model is adopted for the magnetic field and a diffusive equilibrium model is adopted for the plasma density. The details of the model are already described in MUTO *et al.* (1987), MUTO and HAYAKAWA (1987) and ISHIKAWA *et al.* (1989), but only the electron density model is presented in Fig. 4. The ray-tracing computational results are summarized in Fig. 5(a)–(c). Figure 5(a) refers to the case of an initial normalized frequency of $\Lambda_0=0.2$ at the equator (Λ_0, the wave frequency normalized by the gyrofrequency at the starting point), Fig. 5(b), $\Lambda_0=0.3$ and Fig. 5(c) $\Lambda_0=0.4$, respectively. The reason why we have adopted these three frequencies is that the previous observations suggested that the chorus is generated in a frequency range between 0.25 and $0.5 f_{H_{eq}}$ ($f_{H_{eq}}$: the equatorial electron gyrofrequency) (*e.g.*, HAYAKAWA *et al.*, 1989 and the references therein). The initial L value was fixed to $L_0=6.6$ as a typical value in the outer magnetosphere because the observations from this area are discussed in this paper. In each figure, the variation of L value of ray path and the corresponding wave normal direction are plotted as a function of geomagnetic latitude (λ). The corresponding initial wave normal angle (θ_0) is indicated aside each curve. The initial wave normal angles are not restricted to $\theta_0=0°$, but widely varied up to the oblique resonance angle. θ_g is the Gendrin angle at the starting point (the equator) and θ_{inf} is the inflection angle at the starting point (θ_g is definded as the θ angle at which $n \cos \theta$

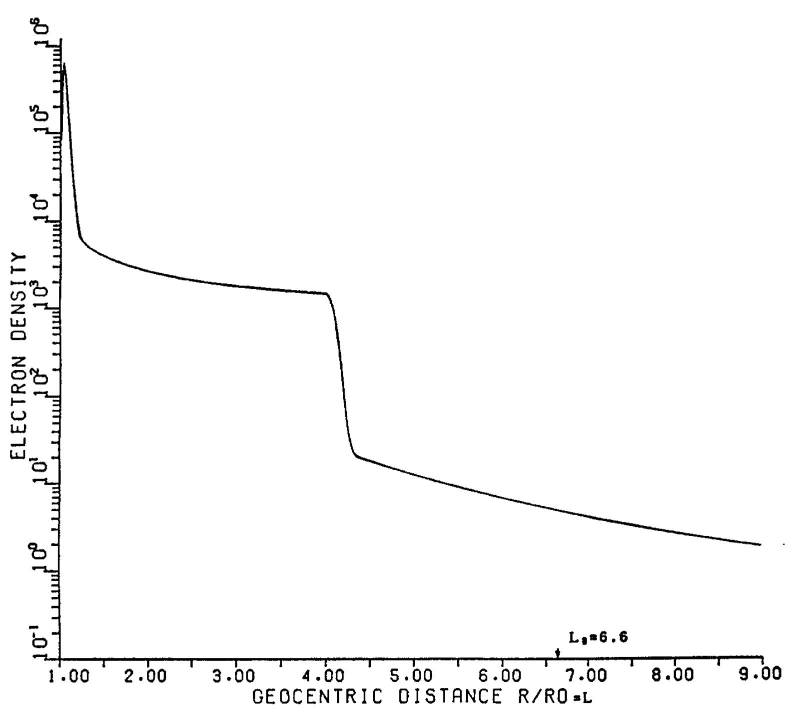

Fig. 4. The electron density model used for the ray-tracing computations.

becomes minimum and correspondingly the ray direction is parallel to the magnetic field. θ_{inf} is the wave normal direction at which the curvature of the refractive index surface changes from convex to concave and correspondingly for which the ray direction makes a maximum angle with the magnetic field. See the details in ISHIKAWA *et al.* (1989)).

In Fig. 5(a) with $\Lambda_0=0.2$, the L value of ray path with $\theta_0=0°$ remains almost on the initial L value for the initial few degrees in the geomagnetic latitude because of a strong focusing along the magnetic field when we consider the shape of the refractive index surface. Then, a subsequent increase in L is noticed, reaching the most outward L value, and then we find a gradual decrease in L value. The ray paths with negative smaller θ_0's are found to exhibit a similar behavior. The wave normal of a ray with $\theta_0=0°$ is found to show an outward rapid shift (*i.e.* increase in ψ value ($\psi=\theta+180°$) defined in Fig. 2) during the initial geomagnetic latitude, and the rate of outward increase of wave normal with latitude becomes smaller at higher latitudes.

In the case of $\Lambda_0=0.3$ as shown in Fig. 5(b), we have a variation in L of a ray path with $\theta_0=0°$ considerably dissimilar to Fig. 5(a) in the sense that the L value remains unchanged during a longer geomagnetic latitude range. On the other hand, the variation of the wave normal direction of a ray with $\theta_0=0°$ shows a very similar behavior as before.

With the increase of Λ_0 up to $\Lambda_0=0.4$ as shown in Fig. 5(c), the ray with $\theta_0=0°$ remains nearly on the initial field line over a considerable latitude range up to 20°. The wave normal direction of the same ray is found to indicate quite a similar behavior.

The behaviors of the wave normal directions are nearly the same for all Λ_0's, and

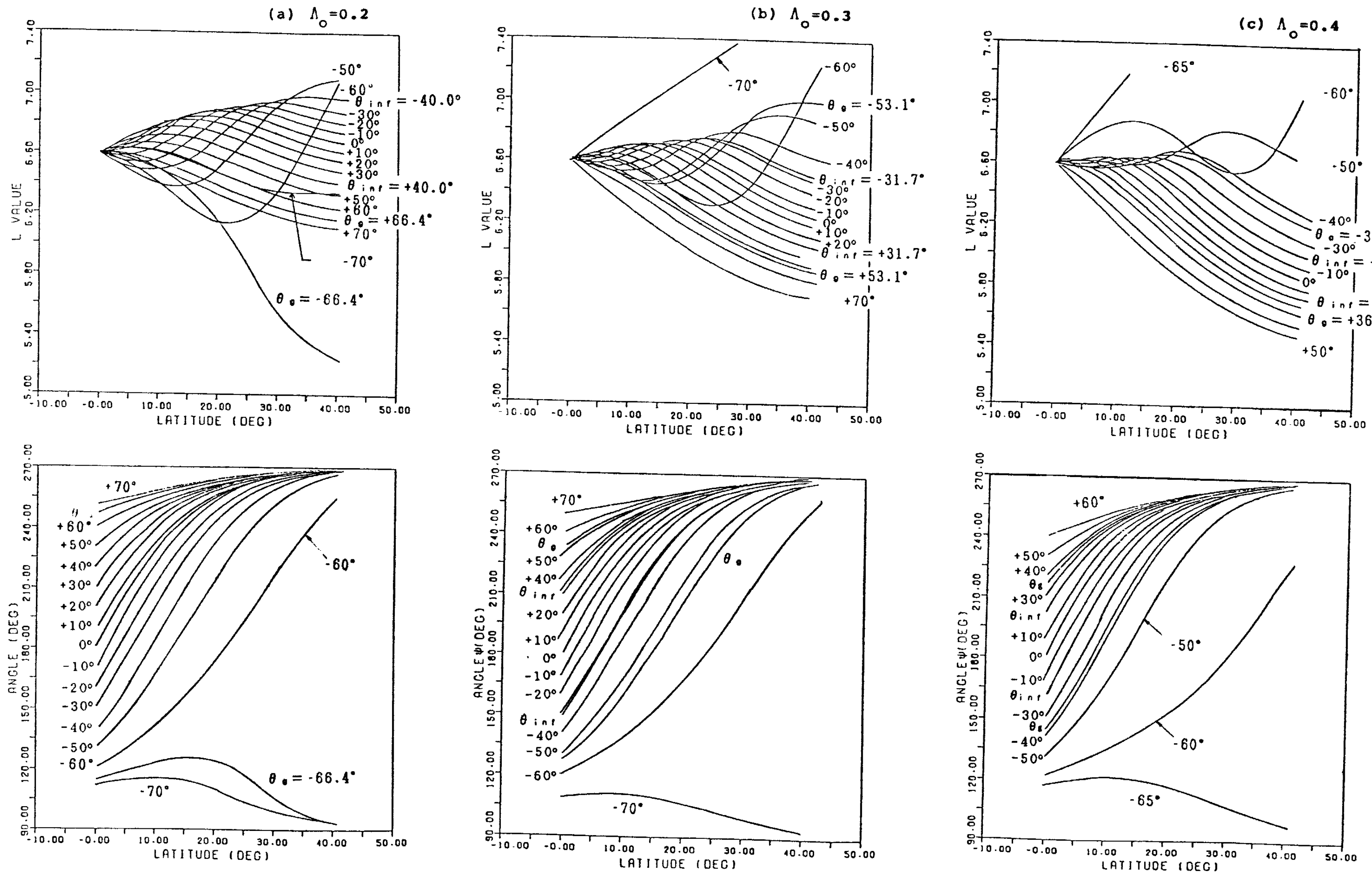

Fig. 5. (*a*) *The ray-tracing result for* $\Lambda_0=0.2$ *in the case of the equatorial wave generation* ($\lambda_0=0°$). *The upper panel illustrates the latitudinal variation of L value of ray path and the corresponding wave normal direction* (ψ) *with initial wave normal angle* θ_0 *as a parameter.* (*b*) *The same as* (*a*) *except for* $\Lambda_0=0.3$, *and* (*c*) *The same as* (*a*) *except for* $\Lambda_0=0.4$.

here we examine the latitudinal variation of wave normal directions by using Fig. 5. The θ values at different latitudes are roughly as follows; $\theta \simeq 25°$ at $\lambda = 5°$, $\theta \simeq 50°$ at $\lambda = 10°$, $\theta \simeq 65°$ at $\lambda = 15°$, $\theta \simeq 74°$ at $\lambda = 20°$, and so forth for $\theta_0 = 0°$. We now compare these values with the observed results in Fig. 1. Even at high latitudes such as $25° < |\lambda| < 45°$, the wave normals are rather well concentrated to $\theta \leqq 30°$ in OGO 5 observation. Also, these θ values are apparently much smaller than the theoretical ray-tracing results as summarized above. Hence, we can conclude that the OGO 5 wave normal results are satisfactorily interpreted in terms of the ducted propagation.

On the other hand, our GEOS 1 results in Fig. 3 are different from those in Fig. 1. Our observing latitude was $\lambda \simeq 18°$ and we read, from Fig. 5, the θ values at $\lambda \simeq 18°$ for all Λ_0 values, and we obtain a range of θ from 60° to 75° when we allow the initial θ_0 to be in a range from $\theta_0 = -20°$ to $\theta_0 = +20°$. The observed θ values are in a range from 30° to 56°, which is found to be smaller than the theoretical values by 20°–30°. TSURUTANI and SMITH (1977) have found that the generation region of dayside chorus is widely distributed around the equator, while the nightside chorus is exclusively generated in the vicinity of the equator. As our observation was carried out at LT$\simeq$10 h, the generation region of chorus is likely to be distributed considerably wide around the equator. Hence, we performed the ray-tracing analyses for the additional two cases of initial generation latitudes; $\lambda_0 = -5°$ and $\lambda_0 = +5°$. Figure 6(a), (b) illustrates the results for a particular $\Lambda_0 = 0.3$ for the wave injection at $\lambda_0 = -5°$ and $\lambda_0 = +5°$, respectively. For $\lambda_0 = -5°$ in Fig. 6(a), the theoretical θ value at the satellite location ($\lambda \simeq 18°$) becomes greater than the observed value, and so we present the results on θ value for $\lambda_0 = +5°$ closer to the observing point in Fig. 6(b) so as to make smaller the discrepancy between the observed and theoretical θ values. When we allow the initial wave normal angle $|\theta_0|$ less than 30°, the theoretical θ values at the observing latitude ($\lambda \simeq 18°$) are found to lie in a range from 33° to 70°, and they are in good agreement with the observed θ values (30°–56°). Hence, our direction finding results in Fig. 3 are likely to be satisfactorily interpreted in term of the non-ducted propagation, though we have to suppose a wide generation region around the equator on the assumption of wave generation with $\theta \leqq 30°$.

If the equator is a well-defined location of the minimum gyrofrequency, the interaction region of $\lambda = +5°$ (+ means the upstream side of the counterstreaming electrons) corresponds to a falling tone and $\lambda = -5°$, a rising tone, based on the accepted gyroresonance interaction model by HELLIWELL (1967). The highly localized nature of nightside chorus around the equator (TSURUTANI and SMITH, 1977) is closely related with the magnetic field structure on the nightside, for which the equator is considered to be a well-defined place of the minimum gyrofrequency. On the other hand, we have a completely different structure of the magnetic field structure on the dayside due to the interaction of the solar wind with the magnetosphere, such that the position of the minimum gyrofrequency is extremely obscure, hence resulting in a wide range of the dayside chorus generation around the equator as found by TSURUTANI and SMITH (1977). Correspondingly, the association of the positive or negative latitude of the interaction region to the falling or rising tone, is not so important in our present study. Assuming the wave emission at $\lambda = +5°$ as described above, has yielded a better agreement with the experimental direction findings, and also $\lambda_0 = +5°$ is more suitable

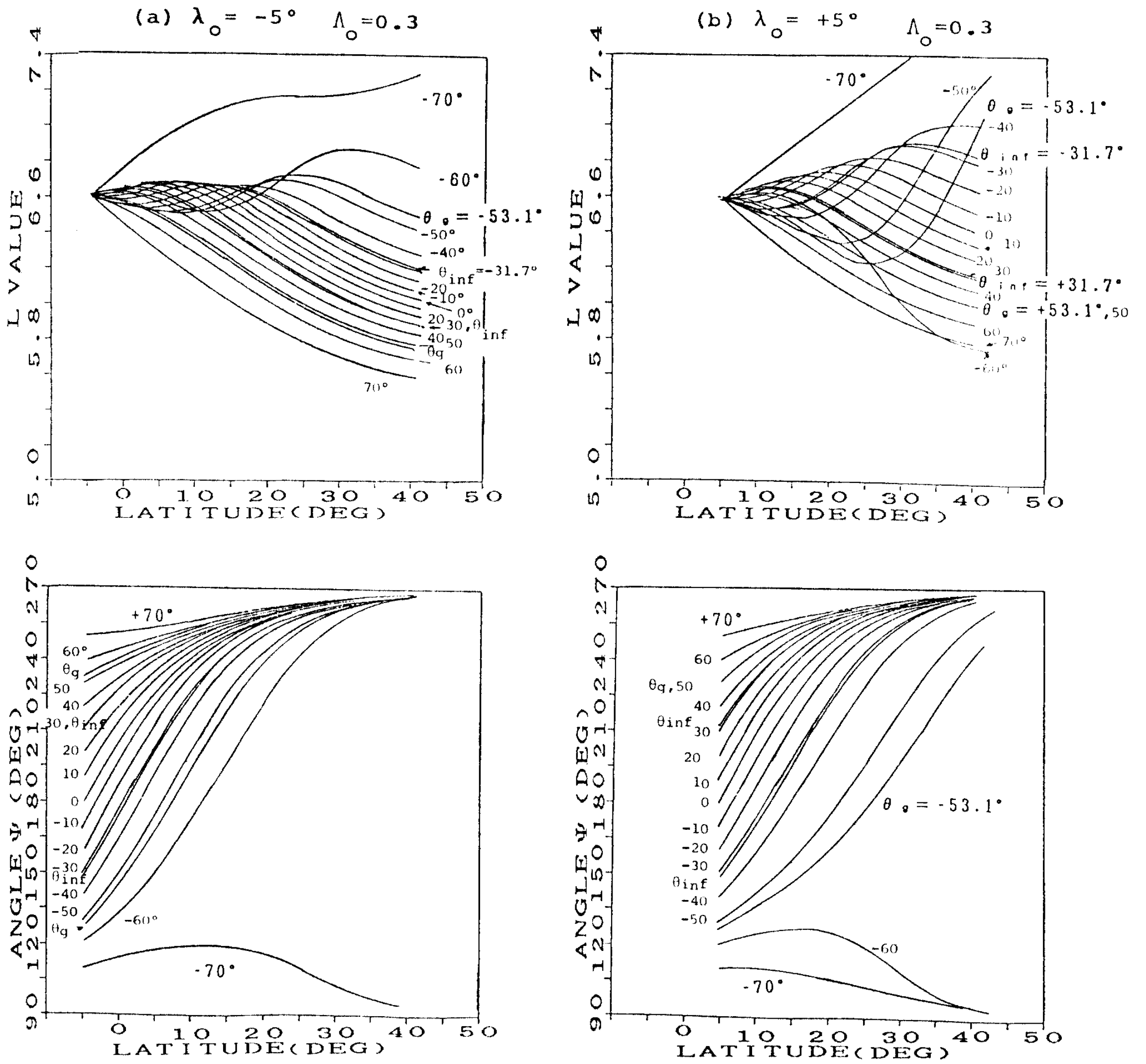

Fig. 6. The ray-tracing results in the case of $\lambda_0 = -5°$ (a) and $\lambda = +5°$ (b) for $\Lambda_0 = 0.3$.

for an increased accessibility to the satellite location than $\lambda_0 = -5°$.

The results of two-dimensional ray-tracing computations presented here are sufficient for the present purpose because the rays with small initial wave normal angles are found to be rapidly focussed into the meridian plane (MUTO *et al.*, 1987; MUTO and HAYAKAWA, 1987) and then the three-dimensional ray-tracing computations are not so essential.

4. Concluding Remarks

The previous direction finding measurements as summarized in HAYAKAWA *et al.* (1989) indicated that chorus emissions are generated in the vicinity of the magnetic equator with nearly longitudinal wave normals. Then, they indicated that those chorus emissions are excited due to the Cyclotron instability by energetic electrons in the outer magnetosphere. The off-equatorial wave normal directions of chorus are discussed in comparison with the corresponding results from two-dimensional ray-tracing analyses in a realistic outer magnetospheric model. The OGO 5 results by BURTON and HOLZER (1974) are interpreted by the ducted propagation by field-aligned ducts after the equatorial generation, while our off-equatorial ($\lambda \simeq 18°$) wave normals on board GEOS 1 (HAYAKAWA *et al.*, 1989) are found to be consistent with the non-ducted propagation after the wave generation with small θ_0's near the equator, together with the inclusion of a wide generation latitude around the equator at 10 h LT.

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