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Brief Reports

Banded Chorus—A New Type of VLF Radiation Observed in the Magnetosphere by OGO 1 and OGO 3

W. J. BURTIS[1] AND R. A. HELLIWELL

Radioscience Laboratory, Stanford University
Stanford, California 94305

Satellites OGO 1 and OGO 3 observe VLF discrete emissions in the magnetosphere primarily in a single, variable frequency band. The frequency f of this 'banded chorus' depends on the equatorial electron gyrofrequency f_{H0} for the field line passing through the satellite, typical ratios of f/f_{H0} being 0.2–0.5. Evidently the emissions are produced near the equator at a fraction of the electron gyrofrequency, as predicted by electron cyclotron resonance generation mechanisms. A secondary dependence of the banded chorus frequency on dipole latitude, such that the lower ratios of f/f_{H0} are found at higher latitudes, is interpreted to mean that the emissions are generated at about half the electron gyrofrequency, but deviate inward from the field line to lower L values as they propagate earthward. Theoretical support is given by ray tracings showing the inward deviation of nonducted whistler-mode radiation due to the curvature of the magnetic field. Banded chorus has been observed at all local times, but is most common in the morning magnetosphere, outside the plasmapause.

INTRODUCTION

The purpose of this paper is to report a new type of very low frequency radiation from the magnetosphere that has been identified with the aid of the OGO 1 and OGO 3 satellites. The observations were made by a broadband VLF receiver, covering the range 0.3 kHz to 12.5 kHz and employing a magnetic loop antenna. (Satellite instrumentation for these two experiments was provided by the Stanford Research Institute [*Rorden et al.*, 1966].) The radiation, called 'banded chorus,' consists of numerous, successive discrete emissions, sometimes accompanied by hiss, in a well-defined band of frequencies. The activity resembles VLF chorus observed on the ground, except that the radiation is limited to a single, often quite narrow band whose center frequency changes with position of the satellite. Noise bursts at frequencies from 100 to 1000 Hz observed by *Russell et al.* [1968] by use of the OGO search coil magnetometer may very likely be the same type of radiation.

It is found that the center frequency of banded chorus varies smoothly with position and is more closely connected with the minimum gyrofrequency along the field line through the satellite than with the local gyrofrequency at the satellite. This behavior is the same as that found for the upper cutoff frequency of both discrete and continuous emissions observed with OGO 1 [*Dunckel and Helliwell*, 1969] and provides further support for the conclusion that the source of the emissions must lie close to the equatorial plane.

In addition to confirming the equatorial origin of banded chorus, the present study shows that the ray path is usually nonducted and is displaced inward with respect to the direction of the earth's magnetic field. It is then found that the frequency of generation of banded chorus is close to one-half the gyrofrequency at the point where the ray path intersects the equator.

RESULTS

Examples of the spectra of banded chorus are shown in Figure 1. These emissions may be of any spectral shape—risers, falling tones, 'hooks,' etc.—but typically one shape is predominant for any given time interval of the order of one

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[1] Present address: NASA/Ames Research Center, Moffett Field, California 94035.

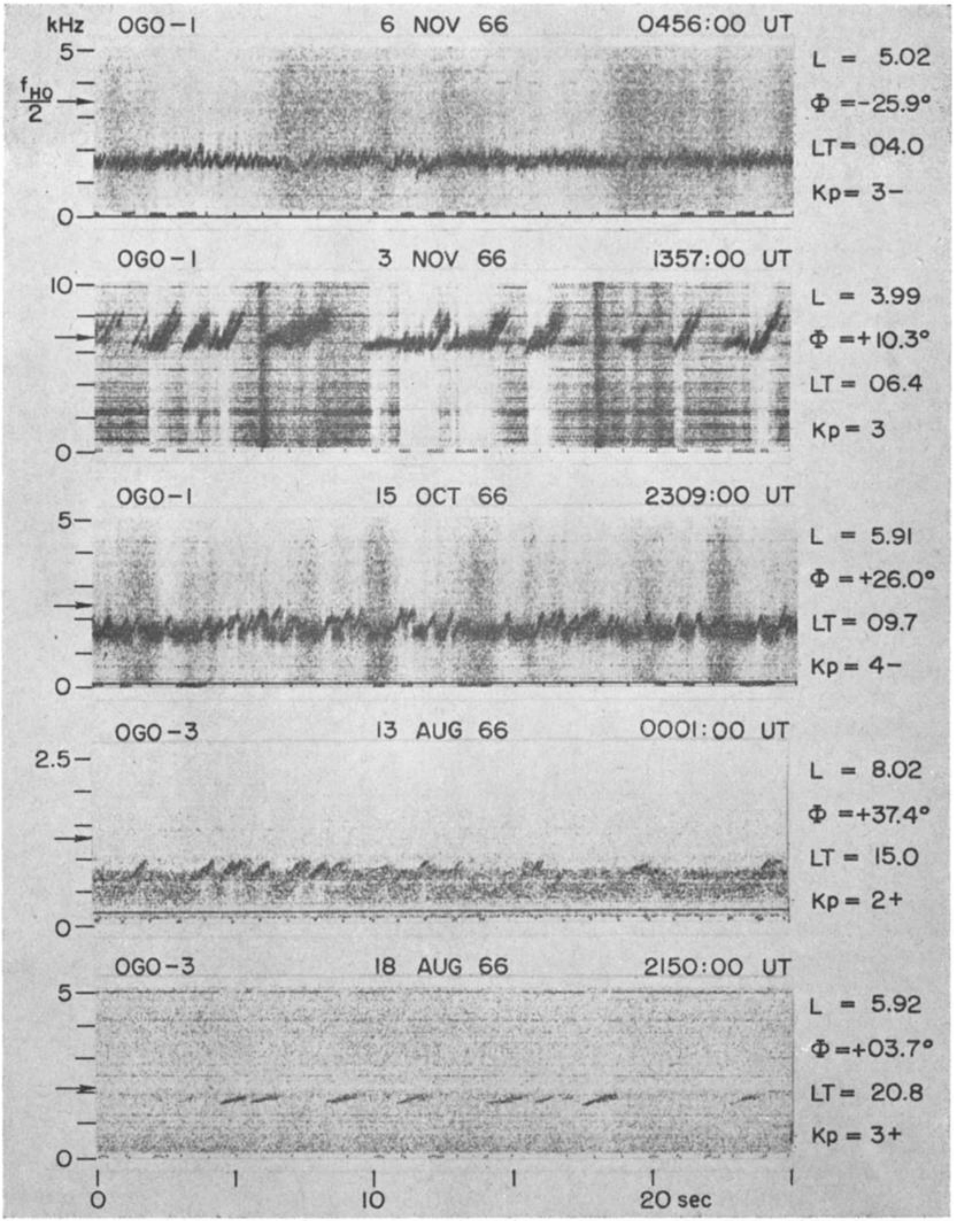

Fig. 1. Five examples of banded chorus observed by OGO 1 and OGO 3, for various (Jensen-Cain) L values, dipole latitudes (ϕ), and local times (LT), showing the confinement of activity to a single frequency band. Vertical enhancements of the background noise in the top three illustrations are caused by telemetry fading. Sudden depressions of the background noise (especially pronounced in Nov. 3, 1966 record) are caused by the AGC of the receiver in responding to enhancements of the intensity of discrete emissions; horizontal lines are interference. Time marks are generated at satellite tracking stations. The arrow on the frequency scale marks the value of $f_{H0}/2$ as determined from the Williams-Mead model.

hour. The discrete emissions typically have a duration of a few tenths of a second, may overlap one another, and may or may not be accompanied by more diffuse, hiss-like noise in the same frequency band. Triggering of the chorus by whistlers or other signals is rarely observed. The individual emissions commonly begin near the frequency of the strongest and most nearly continuous noise, and extend above or below this frequency by varying amounts. The bandwidth of the chorus varies considerably, a typical figure being 20% of the center frequency.

The occurrence of banded chorus will now be briefly described. These remarks are based on 255 hours of broadband VLF data from OGO 1 (29 passes) and OGO 3 (87 passes) over the period June through November 1966. The satellite orbits permit extensive coverage of that portion of the magnetosphere situated between ±40° dipole latitude, at altitudes greater than 2 R_E, for all 24 hours of local time. Banded chorus is a common phenomenon, present about 50% of the time in certain large regions of the magnetosphere. It can occur at any local time, but is most common during local morning, from 0300 to 1500 LT. It is usually observed at L values of 4 or greater, suggesting that this noise is observed primarily outside the plasmasphere [*Carpenter*, 1966]. There is no apparent preference for any dipole latitude between the equator and 40° (roughly the upper limit of satellite positions). Occurrence of banded chorus is positively correlated with magnetic activity, being much more common for $Kp = 2$–4 than for $Kp = 0$–1. Banded chorus radiation was observed in about 90% of the 27 five-minute sampling periods studied between $L = 5$ and $L = 6$, from 0600 to 0900 local time, for $Kp = 2$–4. In general, the occurrence of banded chorus with respect to invariant latitude and time of day resembles roughly that of chorus observed on the ground [*Pope*, 1963].

The outstanding characteristic of banded chorus is that the frequency of the band depends on the location of the satellite. As the satellite moves in space the frequency of the banded chorus slowly and continuously changes. It may range anywhere between the lower and upper cutoffs of the receiver (0.3–12.5 kHz, respectively), depending on the satellite position. This slow spatial frequency variation should not be confused with the rapid, temporal frequency variation of the individual discrete emissions making up the chorus.

An example of this slow variation in frequency is shown in Figure 2 for a typical pass of OGO 1 on September 27, 1966. The satellite was near perigee in the southern hemisphere, moving equatorward, and the L value was slowly decreasing. The spectrogram was made to cover the frequency range where VLF activity was observed, 2–7 kHz, and the banded chorus appears as a dark band, approximately 1 kHz wide, of slowly increasing frequency. Because of the compressed time scale the individual elements of the chorus cannot be distinguished; on an expanded time scale they appear primarily as risers. The vertical 'picket fence' effect results from fading of the telemetry signal induced by the spin of the satellite. The narrow horizontal lines of constant frequency are spacecraft interference.

Also shown in the figure is the variation of the local and equatorial gyrofrequencies, f_H and f_{H0}, as predicted by the (equatorially symmetric) model of *Williams and Mead* [1965], which in this region is essentially the same as the centered dipole model. It is apparent that the VLF banded chorus frequency has a variation similar to the increasing equatorial gyrofrequency, but quite dissimilar to the decreasing local gyrofrequency. The banded chorus frequency varies between about one-quarter and one-half the equatorial electron gyrofrequency f_{H0}.

Equatorial gyrofrequency control of the frequency of banded chorus is evident on nearly all OGO 1 and OGO 3 passes with discrete emission activity. The results for 17 typical passes over a variety of orbits from 1965 through 1967 are summarized in Figure 3. The banded chorus frequency f is plotted as a function of the equatorial gyrofrequency f_{H0}, using the Williams-Mead model to estimate the geometry and strength of the magnetic field. The dots correspond to the frequency of the strongest activity, whereas the bars indicate the range of frequency, from minimum to maximum, when the bandwidth of the chorus exceeded about 1 kHz. As in the case study of Figure 2, the banded chorus frequency is approximately proportional to the equatorial gyrofrequency, the proportionality factor usually lying between one-quarter and one-half. The satellite L value was

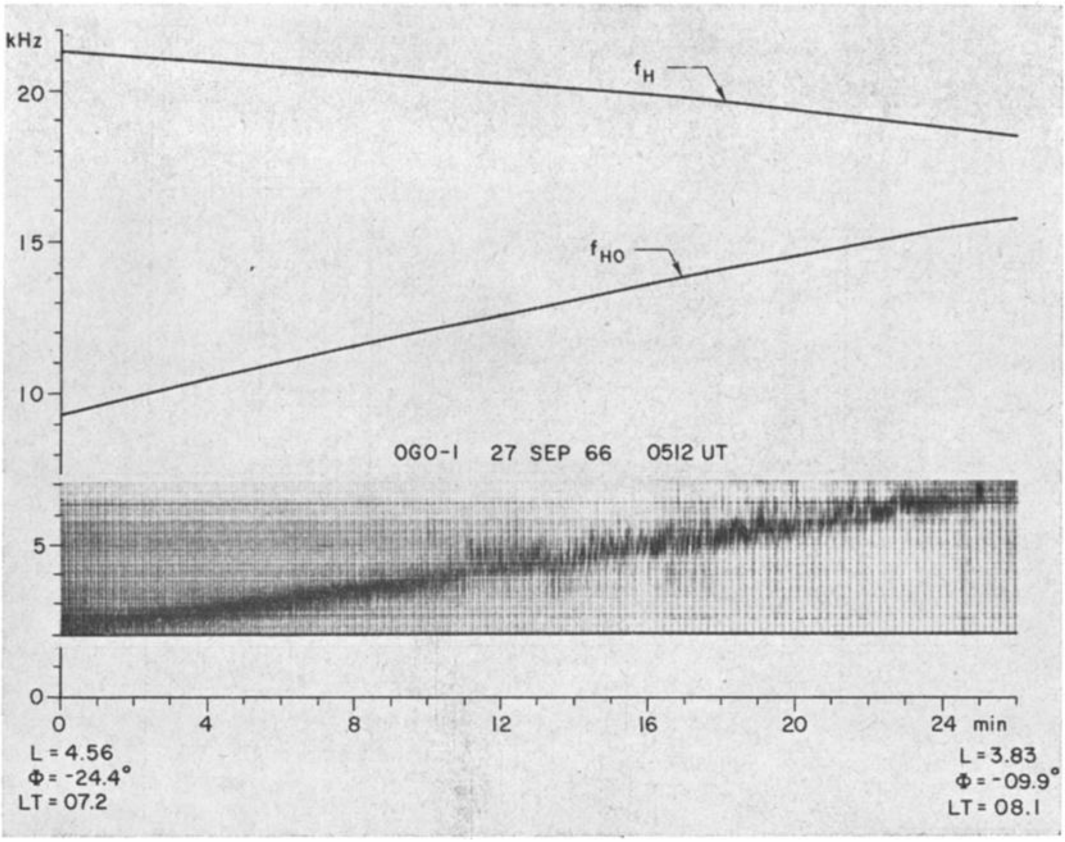

Fig. 2. Part of a typical pass showing the actual variation of the frequency of banded chorus and the estimated variation of the local electron gyrofrequency (f_H) and the equatorial electron gyrofrequency for the field line passing through the satellite (f_{H0}). Vertical and horizontal striations are spurious interference. During this period the only VLF activity observed occurred in the illustrated frequency range of 2–7 kHz, and the banded chorus frequency remained between approximately one-half and one-quarter f_{H0}.

found to have no consistent effect on this proportionality factor. The effect of satellite latitude on this proportionality factor is shown by Figure 5 in which the ratio f/f_{H0} (shown by the dots) is plotted versus latitude. For locations close to the equator the ratio is close to 0.5, dropping to about 0.2 at 40°. It is clear from this figure that some of the spread in the data of Figure 3 is associated with the variation in latitude.

INTERPRETATION

From the close relation of the frequency of banded chorus to f_{H0}, it is inferred that banded chorus is generated near the equatorial plane. This conclusion is the same as that reached on the basis of the study of the upper cutoff frequency of all types (including banded chorus) of whistler-mode emissions observed on OGO 1 [*Dunckel and Helliwell*, 1969].

From the continuity of activity and the smooth variation of the banded chorus frequency with satellite position (Figure 2), it is deduced that the emission sources must be nearly continuously distributed throughout the equatorial plane. Thus if there were significant gaps in the distribution of sources, we could expect to see corresponding gaps in the reception of noise at the satellite. One might argue that the radiation from individual noise sources could spread out so as to fill in the gaps. But then there would be a corresponding spread in

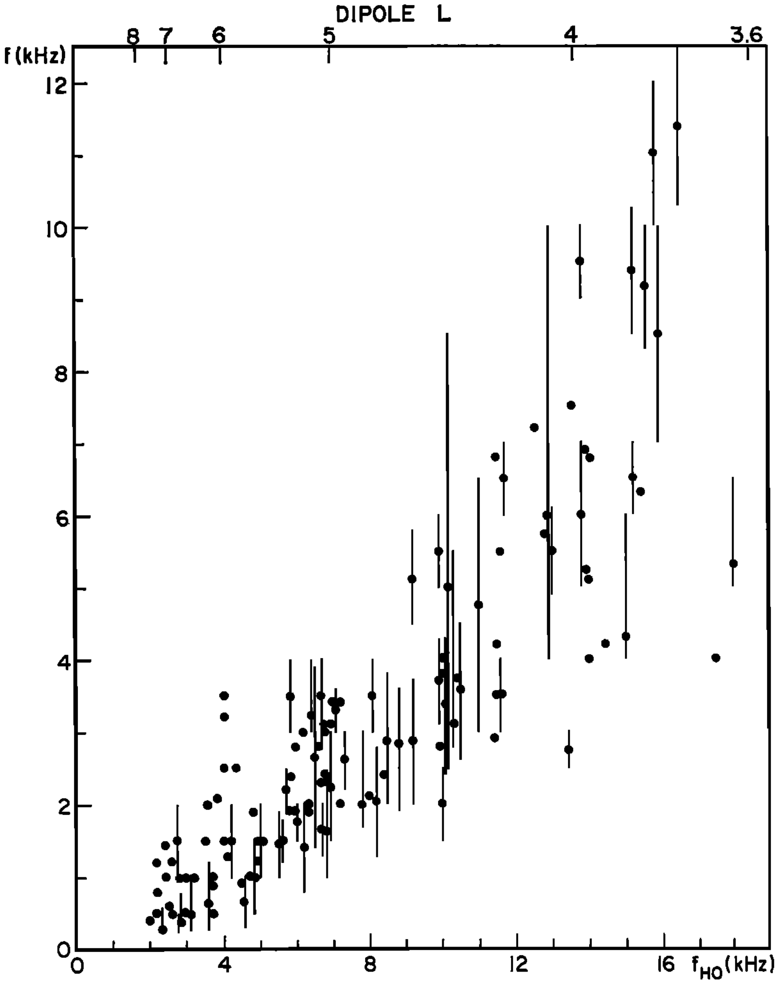

Fig. 3. Summary of the banded chorus frequency (f) as a function of the equatorial gyrofrequency (f_{H0}) for the field line (Williams-Mead model) through the satellite, for 17 typical passes. Dots represent frequency of strongest activity, bars represent bandwidth (bandwidth is less than 1 kHz for dots without bars). The L scale on the upper border is only an approximation, based on the dipole field.

the band of frequencies instead of the relatively narrow band that is seen.

These same continuity properties of the banded chorus can be used to develop models of the propagation paths. Thus to explain a smooth variation of frequency we need a continuous variation in the path structure. This structure could take the form either of nonducted propagation in a smoothly varying magnetosphere, or ducted propagation in a system of very closely spaced field-aligned enhancements of electron concentration. If propagation were nonducted, the wave normal would move toward the transverse direction causing the wave either to be reflected near the lower hybrid resonance frequency [*Thorne and Kennel,* 1967] or to be absorbed in the lower ionosphere through collisional damping [*Helliwell,* 1965]. On the other hand, ducted propagation would permit the energy to cross the lower boundary of the ionosphere and be observed on the ground. Thus the choice of model can be made on the basis of the correlation between the banded chorus observed on high-altitude satellites and chorus observed on the ground. In spite of numerous attempts to find the same discrete emissions on satellite and ground records only three cases of such matched events have been found, and in none of these are the satellite emissions typical of banded chorus. Thus we are led to conclude that the propagation of banded chorus is mainly nonducted.

Although continuity of frequency change has been emphasized, there are cases where the chorus appears in one or more bands whose frequencies are approximately constant for periods of minutes. In Figure 2, for example, there is evidence of irregularity in the banded chorus after 11 minutes. Ducting effects may in fact be responsible for such irregularities.

Having established that propagation is mainly nonducted, we can examine the probable shape of the paths. Assuming a source located in the equatorial plane and propagation in the meridional plane in a model magnetosphere, we can trace the ray path to the satellite for different initial wave normal angles. A set of such paths has been calculated by a computer assuming a model of the magnetosphere in which the electron and proton concentrations varied approximately as the inverse cube of the distance from the earth for the region outside the plasmapause. The starting point for the rays was taken on the equatorial plane at $L = 4$, which is representative of much of the data. The frequency was taken to be one-half the gyrofre-

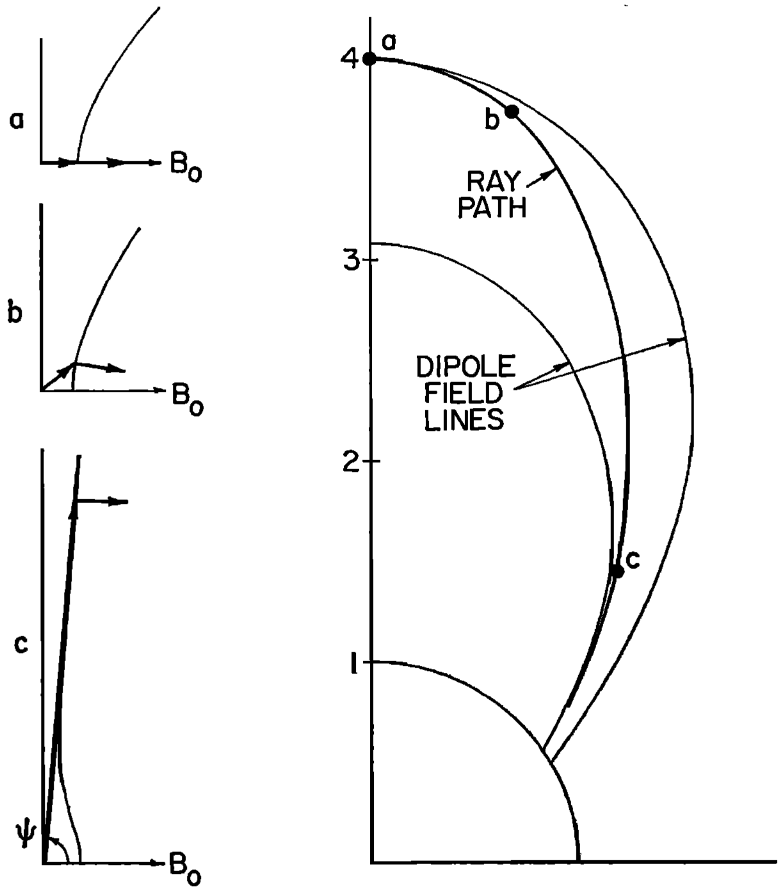

Fig. 4. The computed raypath for a wave generated at the equator at half the electron gyrofrequency and zero wave normal angle. The electron concentration model assumes variation approximately as R^{-3}. Also shown (to scale) are the refractive index surface, wave normal angle ψ, and ray direction for three points on the ray path.

quency at the starting point ($f = 6.86$ kHz). It was found that for most values of the initial wave normal angle, the ray path deviates inward from the field line on which it starts as shown in Figure 4.

This inward deviation of the ray path is opposite to that found by *Thorne and Kennel* [1967] for frequencies small compared with the electron gyrofrequency; the difference is due to the change in topology of the refractive index surface at $f = 0.5\ f_H$. The refractive index surface and wave normal angle ψ are drawn to scale for three points on the ray path in Figure 4. The ray direction (normal to the surface) is at a negative angle to the field at points *b* and *c*. Raypaths for starting frequencies from 0.4 to 0.6 f_{H0} have been computed and found to deviate inward from the field.

The ray tracing results can be expressed in terms of the ratio f/f_{H0} for the ray path as a function of dipole latitude. A set of these curves for various initial wave normal angles is shown in Figure 5. The frequency f is assumed to be half the initial (equatorial) gyrofrequency and constant, while f_{H0} is the equatorial gyrofrequency for the field line intersecting the ray path at a given latitude. Thus decreasing f/f_{H0} indicates inward deviation with respect to a magnetic field line. Also shown in Figure 5 (by the dots) are the experimental data of Figure 3 replotted as a function of dipole latitude. The spread in these data may be attributed to such factors as partial ducting, electron concentration gradients, and magnetic field distortions. There is, however, a significant trend toward lower values of f/f_{H0} at higher latitudes. The general agreement between the data and the model calculations over the ±30° range of initial wave normal angles gives support to the conclusions that (1) the frequency of generation is close to 0.5 f_{H0} and (2) that the ray path in general deviates inward from the dipole field. In addition, the curves seem to fit the data best for small positive initial wave normal angles. This last conclusion is not strong, however, because of the spread in the data and the inaccuracy of the magnetic field and electron concentration models.

DISCUSSION AND CONCLUSIONS

In addition to supporting the results of the satellite study of the upper cutoff frequency of VLF emissions [*Dunckel and Helliwell*, 1969], the new data on banded chorus indicate that the frequency of generation of the nonducted chorus is close to one-half the minimum gyrofrequency on the ray path passing from the equatorial plane to the satellite. This result may be related to the fact that ducted, discrete VLF emissions observed on the ground are commonly triggered at the upper cutoff frequency of nose whistlers, which is known to fall very close to one-half the minimum gyrofrequency [*Carpenter*, 1968]. In addition, the triggering of discrete VLF emissions by Morse-code dashes from VLF stations has also been observed to occur most commonly at one-half the minimum gyrofrequency along the line of force [*Carpenter*, 1968]. Thus the results from the present study suggest that the mechanisms of generation of nonducted and ducted discrete emissions are the same. Should this be the case, then it is clear that ducting itself does not play an essential role in the generation process of ducted emissions.

The preference for frequencies near 0.5 f_{H0} may be related to the topological change in the refractive index surface that occurs at half the electron gyrofrequency. At this frequency and for zero wave normal angle, the curvature of the surface is zero, and maximum ray focusing occurs, improving chances for coherent cyclotron resonance with streaming electrons.

Pitch-angle scattering of energetic particles by broadband VLF radiation in the outer magnetosphere has been postulated by several authors, notably *Kennel and Petschek* [1966], to explain observed energetic particle precipitation. It is supposed that trapped electrons convert part of their transverse kinetic energy to broadband VLF radio energy through a plasma instability occurring at the Doppler-shifted fundamental gyroresonance frequency. This resonance interaction is accompanied by a scattering of the particle pitch angles, which results in precipitation. Although banded chorus may act like broadband energy in pitch-angle scattering, the narrow-band, variable-frequency features of the elements of banded chorus are not explained by the Kennel-Petschek mechanism. It is suggested instead that nonducted banded chorus may be generated by the same mechanism proposed to explain ducted discrete VLF emissions observed on the ground [*Helliwell*, 1967]. Further study of the properties of banded

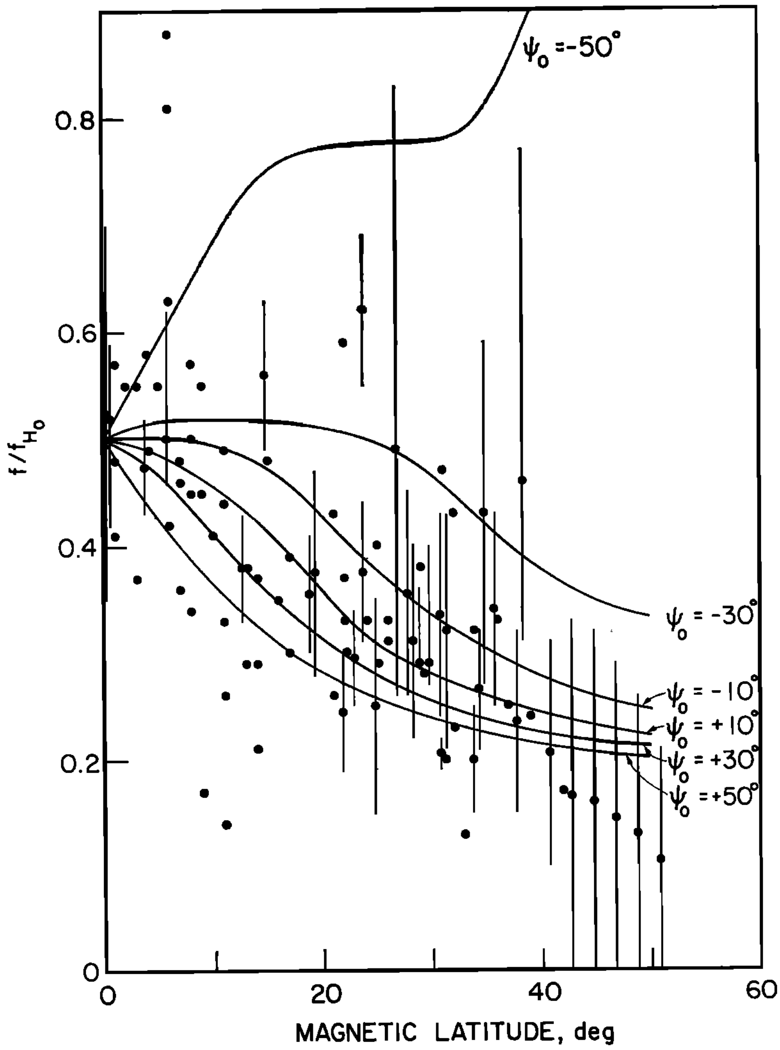

Fig. 5. The dots show the ratio f/f_{H0} for the data shown in Figure 3, plotted versus dipole latitude. The curves show the ratio f/f_{H0} for the computed ray paths that begin at $L = 4$ in the equatorial plane with various values of ψ_0, the initial angle between the wave normal and the magnetic field (measured positively in the outward direction).

chorus, especially the half-gyrofrequency effect, should aid in establishing the mechanism of generation of discrete VLF emissions.

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