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Generation of VLF Radio Noise in the Ionosphere by Energetic Particle Streams

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A. Introduction

The purpose of this paper is to review the mechanisms which have been suggested to explain the VLF radio noise, known as VLF ionospheric noise or VLF emissions (Gallet, 1959), that is believed to originate within the earth's ionosphere. These phenomena include steady noise and relatively short-lived bursts of noise and are found most commonly in the frequency range from 200 to 30,000 cps. They can be observed on the ground and in the ionosphere with an audio amplifier connected to an electric or magnetic antenna.

The amplitude of VLF emissions is comparable to that of whistlers, with spectral power densities measured on the ground ranging from receiver thresholds of about 10^{-18} w/m^2/cps to as high as 10^{-13} w/m^2/cps at the lower frequencies. Higher spectral power densities are observed in the ionosphere, as might be expected, the peak values being of the order of 10^{-12} w/m^2/cps (Gurnett and O'Brien, 1964).

The many varieties of VLF emissions can be classified into two major types.* The first, known as hiss, resembles band-limited thermal noise, and periods of hiss may last from a few seconds to several hours. Hiss may occur in one or more well-defined bands usually not harmonically related. The second type, known as discrete emissions, consists of one or more short bursts of noise that often exhibit a distinctly musical character. The elements of discrete emissions include rising tones, falling tones, hook-shaped forms, and combinations of these. Their frequencies usually range over less than one octave and their duration ranges from less than 1/10th of a second to several seconds.

An emission event consisting of a series of elementary forms repeated at regular intervals is called a "set of periodic emissions" (Helliwell, 1963). Their periods fall mainly within the range of 1.5 to 6 secs. If the period between

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*A detailed classification, with illustrative spectra, is given elsewhere (Helliwell, 1964), together with a comprehensive list of references.

elements varies with frequency, the set is called dispersive; if there is little or no change in period with frequency, the set is called non-dispersive. Often two or more sets of periodic emissions will appear simultaneously, and if they have the same period, they are called multiphase emissions. Sometimes a set of periodic emissions exhibits slow changes in amplitude or a slow drift in frequency, either up or down. A series of closely spaced, usually overlapping, discrete emissions is called "chorus". In one type of chorus each element is a member of a set of periodic emissions. All sets have the same period and are superimposed with such close spacing that the periodicity is often not immediately evident.

An event in which an element or group of elements (such as a set of periodic emissions) is repeated at longer and less regular intervals is called a quasi-periodic emission. This type of emission has also been called a VLF pulsation with long period (Watts, et al, 1963). Both amplitude and center frequency may exhibit systematic variations, with the average period ranging in most cases between 15 and 60 seconds. These are readily distinguished from periodic emissions on the basis of their greater periods.

Emissions may be initiated or triggered by another event such as a whistler, a discrete emission or a signal from a VLF transmitter; these are called "triggered" emissions. Although most triggered emissions follow the apparent source, there is one type, known as a "precursor," that actually precedes the associated whistler.

Emissions appear to be related to whistlers in other ways. Echoing whistlers sometimes develop into bands of periodic emissions. Periodic emissions, furthermore, usually echo with periods exactly equal to the whistler-mode period at the frequency of the emissions.

In addition to their relation with whistlers, VLF emissions show close connections with auroral and magnetic phenomena. In general, emission activity increases with magnetic activity (Storey, 1953; Allcock, 1957), except that at high latitudes when magnetic activity is very great, emission activity decreases (Crouchley and Brice, 1960; Yoshida and Hatanaka, 1962; Pope, 1963) possibly owing to an increase in D-region absorption which reduces the VLF emission activity observable on the ground. Micropulsation activity is also found to increase with the intensity of VLF noise (Westcott el al., 1960; Pope, 1963).

VLF hiss has been found to be associated with sub-visual auroras (Duncan and Ellis, 1959) as well as visual auroras. Aurora-associated hiss usually appears above 4 kc (Martin et al, 1960; Jorgensen and Ungstrup, 1962). Detailed studies of this association indicate that the VLF hiss is most closely associated with auroral arcs and bands, including both those with and without prominent development (Morozumi, 1962).

It is believed that VLF emissions do not arrive from regions external to the earth's atmosphere because of the belief that the outer regions of the magnetosphere cannot support propagation at the frequencies of interest. Hence any VLF noise outside the earth's magnetosphere would have great difficulty penetrating into the propagation region. On the other hand it is conceivable that VLF noise energy might be produced as a result of conversion of some of the kinetic energy of the solar wind near the boundary of the magnetosphere (Sturrock, 1962). As yet this possibility has not been developed in any detail.

More likely sources of energy for VLF emissions are found within the earth's atmosphere. Lightning, which accounts for whistlers, produces sufficient energy but it has not been possible to explain emission phenomenon in terms of lightning alone. Another important source of energy is the trapped-particle radiation within the earth's ionosphere and magnetosphere. From measurements made in satellites, it appears that the energy flux in charged particle streams is many orders of magnitude greater than that in the observed VLF signals. For example, the measurements of electron energy flux for energies $\geq$ 10 Kev made by Gurnett and O'Brien (1964) at the time of a strong VLF emission gave values that were about 10^7 larger than those of the VLF emission. Since trapped particles possess sufficient energy, attention has been concentrated on finding mechanisms for converting this energy to VLF radio noise.

B. Trapped particle mechanisms

One of the earliest attempts to explain VLF noise is based on Cerenkov radiation from individual charged particles streaming along the lines of force of the earth's magnetic field (Ellis, 1957). Cerenkov radiation is emitted by particles which travel at velocities exceeding the phase velocity of electromagnetic waves in the medium. At very low frequencies in the ionosphere and magnetosphere, this requirement is met by the whistler mode in which the wave travels at velocities considerably less than the velocity of light in free space.

The condition for the emission of Cerenkov radiation is that the longitudinal component of the wave velocity equal the particle velocity and is given by

$$\frac{c}{\mu \cos\theta} = v_{||} \quad , \theta > 0 \qquad (1)$$

where $v_{||}$ = particle velocity (assumed to lie in the direction of the earth's field).

μ = wave refractive index

θ = direction of wave propagation with respect to the direction of the earth's field

c = velocity of light in free space

Protons have not been considered as sources of Cerenkov radiation because their number densities are expected to be much less than for electrons.

By considering the form of the refractive index for whistler-mode propagation, the frequencies which will be emitted for given parameters of the medium and stream velocities can be computed. In general, two frequencies will be emitted for any particular set of conditions, and these frequencies are given approximately by

$$f = \frac{f_H\cos\theta}{2}\left\{1 \pm \left[1 - \left(2\frac{f_o}{f_H}\frac{v}{c}\right)^2\right]^{1/2}\right. \qquad (2)$$

where f_o = plasma frequency of the medium of propagation.

f_H = electron gyrofrequency

Estimates of the power spectral densities expected from the Cerenkov mechanism, assuming incoherent radiation, give values of about 10^{-20} w/m^2/cps (Ellis, 1957). This is many orders of magnitude too small to account for the observations (10^{-18} to 10^{-13} w/m^2/cps).

In order to obtain a higher output power by the Cerenkov mechanism, Ungstrup (1964) has proposed that primary auroral particles may produce a large number of secondary electrons in the E region in the energy range 40 - 80 electron volt. He postulates that these secondary electrons could produce sufficient Cerenkov radiation to account for the so-called polar chorus which appears at high latitudes and at a frequency of about 750 cps.

Another single particle mechanism is based on cyclotron radiation from charged particles spiralling about the lines of force of the earth's magnetic field. This radiation can be thought of as the superposition of the radiations of two small dipoles in space and phase quadrature. For non-relativistic electrons, the cyclotron frequency is the upper cutoff frequency for the whistler mode, and consequently little radiation could be expected to be observed on the ground from electrons with zero longitudinal velocity. However, for electrons with a substantial longitudinal velocity, radiation in the backwards direction is doppler-shifted downwards, causing the frequency of the propagating signal to be substantially lower than the ambient gyrofrequency. (Eidman, 1958; Dowden, 1962a). If the longitudinal stream velocity is v and the wave velocity is v_p then it is easily shown that transverse resonance for electrons occurs when

$$v_{||} \cos\theta = -v_p \left(\frac{f_H - f}{f}\right) \tag{3}$$

where v_p = phase velocity

At a frequency equal to one-half the local gyrofrequency, this condition is the same as that for Cerenkov radiation, except for the relative directions of stream and wave velocities. At lower wave frequencies higher stream velocities are required. As a result the top of the path is the most likely region for generation since here the required velocity is a minimum (we therefore expect a maximum in number of particles).

For protons, cyclotron radiation can couple to the right-hand circularly-polarized whistler mode, if the particle's longitudinal velocity exceeds the wave velocity by a small amount so that the particle "sees" a left-hand circularly polarized wave equal to its wave frequency (Kimura, 1961). The resonance condition is

$$v\cos\theta = v_p \left(\frac{f + f_I}{f}\right) \tag{4}$$

where f_I = proton gyrofrequency

An estimate of the power spectral densities expected from cyclotron radiation, assuming incoherent addition of the contributions from individual particles with a density of 1/cc gives a value of about 10^{-21} w/m^2 (Santirocco, 1960). This is also many orders of magnitude too small to account for the observations.

In addition to accounting for the observed intensities, any satisfactory theory must also account for the spectral characteristics of emissions. To explain the short duration of many types of emissions, it has been supposed that the generating particles occur in bunches of small length. However, such bunches have not yet been observed and it is difficult to explain how they could be formed and maintained for any appreciable length of time (Gallet, 1959). An explanation of "hooks" based on doppler-shifted cyclotron radiation from a particle bunch (Dowden, 1962a) has been found to disagree with experimental data (Brice, 1962).

The limitations of the particle bunch hypothesis have led to consideration of mechanisms involving collective interaction among the streaming particles. One, is the so-called traveling-wave-tube (TWT) mechanism in which a stream of electrons trapped in the earth's field acts like the beam in a traveling-wave tube, and the low velocity whistler-mode wave is the analog of the slow wave of the traveling-wave tube. (Gallet and Helliwell, 1959). A necessary condition for amplification in this mechanism, which is based on longitudinal resonance, is that the Cerenkov condition of (1) be satisfied. Coupling between the wave and the electrons in the stream is provided by the small longitudinal component of electric field which exists when the wave-normal direction is not longitudinal. The relationship between the wave electric field and the force on the electrons is sketched in Fig. 1a. Although growth of a longitudinal electric wave has been established for this mechanism (Bell and Helliwell, 1960; Barrington, 1960), it is not clear that the whistler mode can couple efficiently into this growing wave under normal conditions (Barrington, 1960). An alternative mechanism, in which the stream and wave travel in the same direction, is one in which amplification takes place on a beam of protons carrying a slow cyclotron wave (M. A. Gintsburg, 1960; Maeda and Kimura, 1962).

Another collective interaction is based on transverse resonance between the wave and gyrating electrons (Brice, 1963). The relationship between the wave magnetic field and the electrons is sketched in Fig. 1b. The resonance condition is the same as for doppler-shifted cyclotron radiation. It has been found that under certain conditions realizable in the magnetosphere this transverse resonance can lead to an instability that might account for the generation of VLF emissions (Bell and Buneman, 1964). In this mechanism the emitted radiation encounters new electrons moving into the interaction region because the stream and wave velocities are oppositely directed. Thus modification of the particle distribution can be produced by the emitted radiation itself. The disturbance in this case is non-convective and is characteristic of oscillators whereas in the TWT mechanism, the disturbance is convective and is characteristic of amplifiers (Sturrock, 1958). The strong feedback inherent in the nonconvective instability might permit significant changes in the distribution of the incoming particles and lead to large changes in the frequency and amplitude of the disturbance. Furthermore, the duration of the emission would be limited only by the supply of particles and the form of the emitted radiation.

As a means of triggering an instability in a geomagnetically-trapped particle stream, it may be postulated that a strong whistler-mode wave may modify the distribution of the particles in an existing stream sufficiently to produce an instability (Helliwell, 1963). In the case of longitudinal resonance, it seems possible that the longitudinal component of the wave's electric field might trap those particles which satisfy the condition for longitudinal resonance, thereby building up a stream of resonant particles which when subsequently released from the wave could act as a source for traveling-wave amplification. In the analogous case for the transverse resonance, the magnetic field of the wave would organize the particles as shown in Fig. 1b, so that the phase of each gyrating particle matches the phase of the propagating wave (Brice, 1963). Possible advantages of this type of organization over that based on longitudinal resonance are that there is no bunching of the charges, as Fig. 1b shows, and that it is operative for purely longitudinal whistler-mode propagation whereas the longitudinal interaction is not.

C. Comparison of observations with theories

The steady noise, or hiss, could be explained on the basis of either the longitudinal or transverse resonances for electrons. Hiss is seen at high latitudes, such as Byrd Station, up to frequencies well in excess of 30 kc/s. Assuming propagation on lines of force close to the observing station, it is difficult to explain these high frequencies in terms of any mechanism operating near the top of the line of force. Thus at Byrd Station the line of force has a minimum gyrofrequency of 1.5 kc/s, and therefore, one could not expect to observe on the ground any radiation from the top of the line of force at frequencies exceeding this value. In the TWT mechanism the required stream velocities vary inversely with refractive index, as shown by (1) whereas in the transverse-resonance mechanism, the stream velocities are nearly proportional to f_H, for large f_H, as shown by (3). Thus VLF noise generated in the ionosphere would be more readily explained in terms of longitudinal resonance, whereas noise generated where the wave frequency is comparable with the local gyrofrequency is more readily explained in terms of transverse resonance.

To explain discrete emissions in terms of the TWT mechanism, it is supposed that the stream consists of a particle bunch limited in length to several wavelengths. As the bunch moves along a line of force, it amplifies the components of the input noise which satisfy (2). However, no mechanism for producing the required bunch of particles has yet been demonstrated. For either resonance unless the input wave normals or input frequencies were limited to a narrow range, the output should cover a relatively broad range of frequencies. Another feature of the discrete emissions is their duration, which though often much less than a second, may continue without interruption for as long as 20 seconds. Brice has shown (private correspondence) that for convective mechanisms in which the bunch velocity matches the wave phase velocity, the maximum duration of a discrete constant frequency emission is less than the whistler group delay at the same frequency. Analysis of the path of propagation in one particular case showed that if the emission were produced by such a convective disturbance its duration would be less than 3 sec. as compared with the observed value of 20 seconds. The non-convective transverse interaction on the other hand is potentially capable of generating an emission whose duration is unlimited. As long as the flow of particles continues, and as long as the interaction mechanism is operating, then it is possible for emissions to be produced.

Periodic emissions have been interpreted in terms of particle bunches bounding between their magnetic mirror points (Pope and Campbell, 1960; Dowden, 1962b). Later work showed that the period of periodic emissions was the whistler-mode period and that trains of these periodic emissions could be started by whistlers (Helliwell, 1963). This suggests that generation occurs whenever the whistler-mode echo of an emission passes through the interaction region. On the basis of these observations, it was concluded that the energy source must be continuously present during the period of observation of the periodic emissions, implying the continuous presence of a suitable flux of charged particles. In this way we can understand the production of non-dispersive periodic emissions for periods as long as several hours. Dispersive periodic emissions are naturally explained as the superposition of triggered elements and the whistler-mode echoes of previous elements.

Chorus is more difficult to expalin than the periodic emissions. Chorus usually consists of short, well-defined discrete elements often overlapping in time, with spacings as small as a tenth of a second. Some examples of chorus are readily explained as the superposition of many sets of periodic emissions all having the same period. On other occasions, however, it appears that the chorus elements are not simply generated through triggering by the whistler-mode echo of a previous element but are successively generated by some other process. Again the transverse gyroresonance instability offers a possible basis for explanation.

It is suggested that because the development of an instability requires a certain kind of particle distribution and because the particle distribution will change during the production of an emission, there may be a "relaxation" time required for the stream distribution to achieve an unstable form. In this way one can explain the sequence of the similar but not identical elements found in chorus.

In the Arctic and Antarctic a very-low-frequency emission sometimes called polar chorus appears primarily during daytime and during local summer. The dissimilarity in the temporal variations of polar chorus at the two ends of the line of force suggests a local origin. According to the mechanism of secondary particle emission (Ungstrup, 1964), the frequency of the polar chorus should vary with the critical frequency of the E region. However no definite evidence on this relation is yet available. Another explanation for polar chorus is based on cyclotron radiation from protons in the ionosphere (Aarons, et al, 1960). However, this radiation is opposite in sense of polarization to that of the whistler-mode and it is therefore difficult to see how it could escape from the ionosphere.

Quasi-periodic emissions, showing periods much greater than the normal whistler-mode period, have not yet been explained. However, it is known that they often consist of groups of periodic emissions whose spectrum shows the quasi-periodic fluctuation. The quasi-periodic emissions have on occasion been found to correlate with micropulsations and so may be related in some way to periodic fluctuations in the strength of the earth's magnetic field. On the other hand in some cases the quasi-periodicity appears to be related to dispersion of the elements of the periodic emissions, suggesting that the mechanism of periodic emission might account for the fluctuations.

Triggered emissions provide the clearest evidence that the conditions for emission are omnipresent over long periods of time in the ionosphere. A suitable signal passing through the region then produces the conditions required for the development of an instability. Virtually all known forms of emissions have on occasion been observed to begin in whistlers or in signals transmitted by fixed frequency stations. It is important to note that the production of an emission may depend critically on the duration of the triggering signal (Helliwell, et al, 1964). Specifically it has been found in the case of artificially-stimulated emissions that the triggering signal must exceed 50 ms in duration in order to produce an emission. In many cases it has been found that the Morse Code dashes from VLF transmitters, lasting about 150 ms produce reliable triggering throughout a period of general triggering activity. On some occasions it has been observed that whisltres do not trigger emissions until the duration of their echoes within a certain limited frequency band is greater than 150 ms. Thus it appears that there is a characteristic "pumping" time for an instability which is triggered by a passing whistler-mode wave packet. Recent theoretical work based on a linearized solution of the Boltzmann-Vlasov equation (Bell and Buneman, 1964) has shown that the transverse gyroresonance instability can in fact exist under conditions thought to exist in the magnetosphere. The triggering wave packet is thought to produce temporarily the conditions required for growth of the instability. On the other hand when the natural stream has the required properties, an instability develops spontaneously and is repeated at intervals determined by the stream "recovery" time. The magnitude and spectral shapes of discrete emissions have not yet been predicted by theory, which will probably require a non-linear analysis.

D. Conclusion

In this paper we have reviewed the theories and experiments involved in the generation of VLF radio noise in the ionosphere by energetic particle streams. It has been shown that the existing particle streams carry adequate amounts of kinetic energy to provide a source for the observed emissions. Mechanisms are available to account qualitatively, at least, for all of the observed noises. Cerenkov radiation from secondary electrons in the ionosphere may be able to account for the particular kind of noise known as polar chorus. TWT amplification as well as the transverse gyroresonance instability could account for hiss. The transverse gyroresonance instability operating near the top of the path provides the easiest explanation for discrete emissions.

Although qualitative mechanisms have been proposed, none of these has been quantitatively treated in such a way as to provide a detailed explanation for the observed amplitudes and spectral shapes of discrete emissions. A useful next step therefore would be the further development of the theory to account for the entire history of an emission.

In order to test any theory of the production of an emission the parameters of the stream will have to be known in more detail than is presently available. Thus the distributions of energies and pitch angles of particles in the stream must be known as well as the stream's location in space. These data might be obtained with a satellite which is also equipped to observe VLF noise. However, it may be difficult to relate a particular observed noise burst to a particular stream because of the possibility that the noise may propagate from a region of origin considerably removed from the location of observation.

Emission excitation experiments controlled from the ground (or even from a rocket or satellite) offer good possibilities for determing the properties of triggered emissions. With a controlled source it should be possible to determine precisely the required power and duration of the exciting signal. In addition by transmitting triggering pulses with different spacings in time, it should be possible to determine the relaxation time of the medium. Furthermore, with a variable frequency source the dependence of emission characteristics on the spectrum of the exciting signal could be measured. On the basis of available information we would need for these experiments a transmitter covering the frequency range 3 to 30 kc/s and with an output power of at least 10 kilowatts. It should be located at a geomagnetic latitude between 55^o and 70^o.

In this paper we have dwelt primarily on the problem of understanding the generation of VLF radio noise. The mechanisms considered have centered around the conversion of particle kinetic energy to electromagnetic wave energy. It should be noted that this process can be reversed. Through the mechanism of gyro-resonance, it is possible in principle either to accelerate or decelerate the resonant particles with a whistler-mode wave (Helliwell and Bell, 1960; Parker, 1961; Dungey, 1963; Bell, 1964; Cornwall, 1964). This mechanism may be of some importance in the creation and removal of relativistic particles from the radiation belts. Should the efficiency of this kind of coupling be high, then controlled VLF waves might be used to modify the distribution of energetic particles trapped in the earth's magnetic field. New kinds of experiments would then be possible.

REFERENCES

Aarons, J., G. Gustafsson, and A. Egeland, 1960, "Correlation of Audio-frequency Electromagnetic Radiation with Auroral Zone Micropulsations, Nature, 185 (4707), 148-151 (Jan. 16).

Barrington, R. E., 1960, "The Interaction of the Whistler Mode with the Space Charge Modes of an Electron Stream," Proc. Symp. on Physical Processes in Sun-Earth Environment, 20-21 July 1959, DRTE Publication 1025, Defence Research Telecommunications Establishment, Ottawa, Canada, 223-240 (Mar.).

Bell, T. F. and O. Buneman, 1964, "Plasma Instability in the Whistler Mode Caused by a Gyrating Electron Stresm," Phys. Rev., 133 (5A), 25-26, March 2, 1964.

Bell, T. F. and R. A. Helliwell, 1960, "Traveling-Wave Amplification in the Ionosphere," Proc. Symp. Phys. Processes in the Sun-Earth Environment, 20-21 July, 1959, Defence Res. Bd., Dept. of Nat'l. Def., Ottawa, Canada, DRTE No. 1025, 215-222 (Mar.).

Brice, N.M., 1962, "Discussion of Paper by R. L. Dowden, 'Doppler-Shifted Cyclotron Radiation from Electrons: A Theory of Very Low Frequency Emissions from the Exosphere," J. Geophys. Res., 67(12), 4897-4899 (Nov.). 1963, "An Explanation of Triggered VLF Emissions," J.Geophys. Res., 68(15), 4626-4628, (Aug. 1).

Cornwall, J. M., 1964, "Scattering of Energetic Trapped Electrons by Very-Low-Frequency Waves," J. Geophys, Res., 69 (7), 1251-1258 (April 1).

Crouchley, J. and N. M. Brice, 1960, "A Study of 'Chorus' Observed at Australian Stations," Planet. Space Sci., 2(4), 238-245 (Aug.).

Dowden, R. L. 1962a, "Doppler-Shifted Cyclotron Radiation from Electrons: A Theory of Very Low Frequency Emissions from the Exosphere," J. Geophys. Res., 67(5), 1745-1750 (May).
1962b, "Very-Low-Frequency Discrete Emissions Received at Conjugate Points," Nature, 195(4836), 64-65 (July 7).

Duncan, R. A. and G. R. A. Ellis, 1959, "Simultaneous Occurrence of Sub-Visual Aurorae and Radio Noise Bursts on 4.6 Kc/s," Nature, 183, 1618-1619 (June 6).

Dungey, J. W., 1963, "Loss of Van Allen Electrons Due to Whistlers," Planet. Space Sci., 11(6), 591-595 (June).

Eidman, V. Ia., 1958, "The Radiation from an Electron Moving in a Magnetoactive Plasma," J.Expl. Theoret. Phys. (USSR), 34, 131-318 (Jan.). also in Soviet Physics JETP, 34 (7), No. 1, 91-95 (July) (English Translation).

Ellis, G. R. A., 1957, "Low Frequency Radio Emission from Aurorae," J. Atmos. Terr. Phys., 10, 302-306.

Gallet, R. M., 1959, "The Very Low Frequency Emissions Generated in the Earth's Exosphere," Proc. IRE, 47(2), 211-231 (Feb.).

Gallet, R. M. and R. A. Helliwell, 1959, "Origin of 'Very Low Frequency' Emissions," J. Res. NBS, 63D(1), 21-27 (July-Aug.).

Gintsburg, M. A., 1960, "On the Possibility of Exciting Radio Waves by Solar Corpuscular Streams", Radiophysica, Izvestija Vuzov, 3(6), 983-988.

Gurnett, D. A. and B. J. O'Brien, 1964, "High-Latitude Geophysical Studies with Satellite Injun 3. 5. Very-Low-Frequency Electromagnetic Radiation," J. Geophys. Res., 69(1), 65-89, (Jan. 1).

Helliwell, R. A., 1963, "Whistler-Triggered Periodic VLF Emissions," J. Geophys. Res., 68(19), 5387-5395 (Oct. 1).

Helliwell, R. A., 1964, "Whistlers and Related Ionospheric Phenomena", Stanford University Press, Stanford, Calif., (in press).

Helliwell, R. A. and T. F. Bell, 1960, "A New Mechanism for Accelerating Electrons in the Outer Ionosphere," J. Geophys. Res., 65(6), 1839-1842.

Jorgensen, T. S. and E. Ungstrup, 1962, "Direct Observation of Correlation between Aurorae and Hiss in Greenland," Nature, 194 (4827), 462-463 (May 5).

Kimura, I., 1961, "Amplification of the VLF Electromagnetic Wave by a Proton Beam through the Exosphere. An Origin of the VLF Emissions," Rep. Ionos. Space Res. Japan, 15(2), 171-191 (June).

Maeda, K. and I. Kimura, 1962, "Amplification of the VLF Electromagnetic Wave by a Proton Beam through the Exosphere," J.Phys. Soc. Japan, 17 (Supplement A-II), 92-95 (Jan.).

Martin, L. H., R. A. Helliwell, and K. E. Marks, 1960, "Association between Aurorae and Very-Low-Frequency Hiss Observed at Byrd Station, Antarctica," Nature, 187(4739), 751-753 (Aug. 27).

Morozumi, H., 1962, "A Study of the Aurora Australis in Connection with Association between VLFE Hiss and Auroral Arcs and Bands Observed at the South Geographical Pole 1960," State University of Iowa, Iowa City, Iowa, SUI 62-14 (Aug.).

Parker, E. N., 1961, "Transresonant Electron Acceleration," J. Geophys. Res., 66(9), 2673-2676 (Sept.).

Pope, J. H., 1963, "A High-Latitude Investigation of the Natural Very-Low-Frequency Electromagnetic Radiation Known as Chorus," J. Geophys. Res., 68(1), 83-99 (Jan. 1).

Pope, J. H. and W. H. Campbell, 1960, "Observations of a Unique VLF Emission," J. Geophys. Res., 65(8), 2543-2544 (Aug.).

Santirocco, R. A., 1960, "Energy Fluxes from the Cyclotron Radiation Model of VLF Radio Emission," Proc. IRE, 48(9), 1650 (Sept.).

Storey, L. R. O., 1953, "An Investigation of Whistling Atmospherics," Phil. Trans. Roy. Soc. A, 246, 113-141.

Sturrock, P. A., 1958, "Kinematics of Growing Waves," Phys. Rev., 112(5), (Dec. 1).
1962, "Generation of Radio Noise in the Vicinity of Earth," J. Res. NBS, 66D (2), 153-157 (Mar.-Apr.).

Ungstrup, E., 1964, "High Latitude VLF Radio Emissions Generated in the Ionosphere," Paper presented at the AGU Meeting, April 21-24, 1964, Wash. D. C., Abstract in Trans. Amer. Geophys. Union 45(1), 49 (March).

Watts, J. M., J. A. Koch and R. M. Gallet, 1963, "Observations and Results from the 'Hiss Recorder' and Instrument to Continuously Observe the VLF Emissions," J. Res. NBS, 67D(5), 569-579 (Sept.-Oct.).

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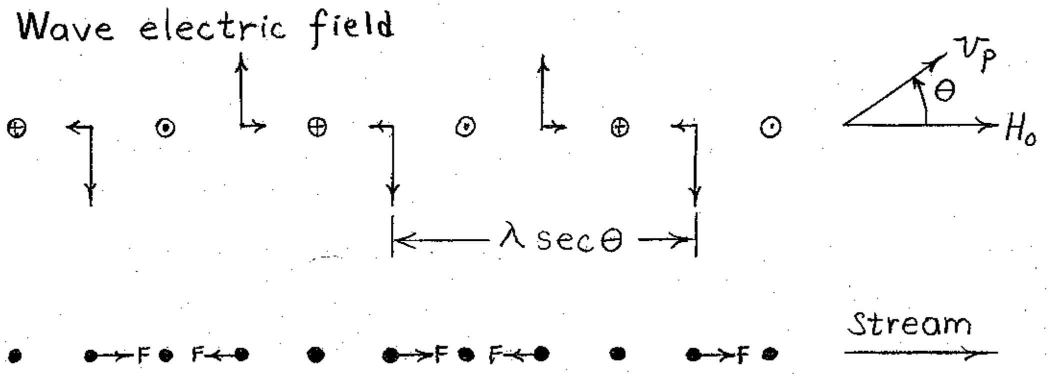
a) LONGITUDINAL RESONANCE



b) TRANSVERSE RESONANCE

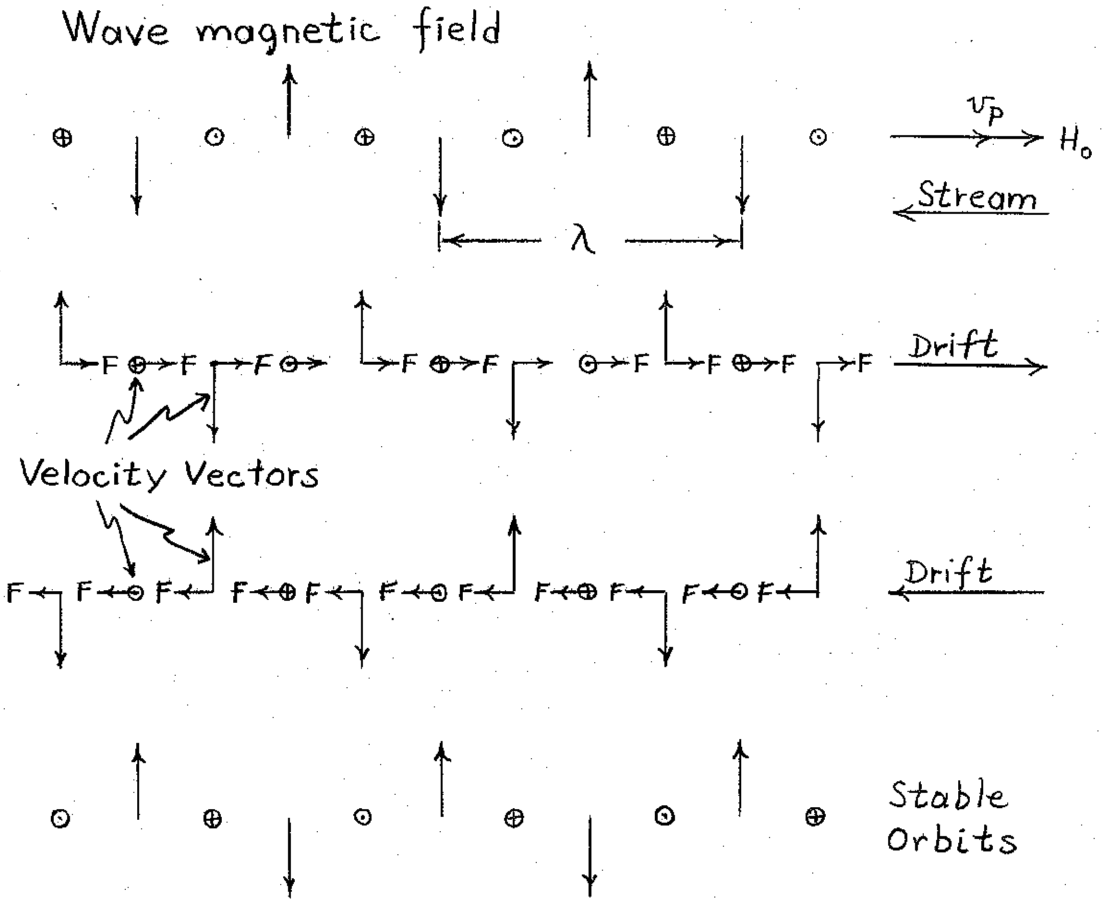


Figure 1 Forces on electrons due to wave fields. Force vectors are horizontal.