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REVIEW ON RADIO NOISE OF NATURAL ORIGIN

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ABSTRACT

This report consists of a comprehensive review of past work on the subject of radio noise of natural origin and is conveniently divided into two major portions. Part I is concerned with the radio noise in the ionosphere and Part II is concerned with the solar radio noise from the sun. It is well known that the radio noise of natural origin from the ionosphere can be divided into two general categories--nonthermal and thermal (Section 1.7). The former includes whistlers, very-low-frequency (VLF) and extremely-low-frequency (ELF) emission.

The purpose of the present review is to outline and summarize previous work on the subject of generation and propagation of naturally occurring radio noise from the ionosphere and from the sun, and to determine the applicability of the nonlinear microwave tube interaction theories to the study of these natural phenomena.

TABLE OF CONTENTS

I. RADIO NOISE IN THE IONOSPHERE

1.1 Classification and Characteristics of VLF Noise

At frequencies between approximately 200 cps and 30 kc/s there occurs radio noise of natural origin known as "Atmospheric Whistler" and "VLF Emission" (also called "VLF ionospheric noise").

From the examination of a large quantity of high resolution spectrograms, it has been deduced[1] that a major fraction of "VLF Emission" is excited in the exosphere by streams and bunches of high-speed ionized particles precipitating into the ionized atmosphere in the presence of the earth's magnetic field. The electromagnetic waves excited are then propagated in the manner of whistlers. A systematic classification of observed VLF noise can be given as follows:

1.1.1 Whistlers. Whistlers result from the dispersive propagation, over a very long path, of very low frequency electromagnetic waves radiated by lightning impulses. Through the action of free electrons in the outer ionosphere they are believed to follow horseshoe-shaped paths defined by the earth's magnetic field, traveling from one hemisphere to the other in a time of the order of one second. All frequencies are emitted at once.

1.1.2 VLF Emissions. It is believed that VLF emissions are not caused by lightning and are strongly associated to magnetic perturbations. There are two principal types:

1. Continuous in both time and frequency. Steady-state situation (e.g., Hiss).

2. Discrete, but often of a repetitive nature. Transient situation, e.g., Hook, Raisers, Quasi-Vertical (chorus), falling-tones, Quasi-horizontal, pseudo noses, etc.

1.1.3 Interaction Between Whistlers and VLF Emissions.

The interaction involves either the continuous or the discrete VLF Emissions.

The origin and characteristics of whistlers are relatively well understood[2]. VLF emissions, on the other hand, appear to originate within the ionosphere and although many types are recognized no satisfactory theory of their origin has yet been advanced.

1.2 Mechanisms of Generation of VLF Emissions

With the relatively small amount of information so far available, any discussion of the origin of terrestrial VLF noise bursts must be largely speculative. Nevertheless over the past decade considerable effort has been expended on the essentially similar problem of explaining solar radio noise bursts. These are generally believed to originate in the interaction between fast-streams of charge particles and the plasma of the solar corona, and the suggested mechanism includes plasma oscillations, gyro and synchrotron radiation and Cerenkov radiation[3,4]. Similarly one might expect that the interaction between auroral particle streams and the plasma of the outer-atmosphere of the earth would also produce radio noise. The gyro-frequency and plasma frequency in this region are such that the wave frequency of noise generated by any of the above processes would be in the kc/s to mc/s range, rather than tens or hundreds mc/s as from the sun. The main difference lies in the position of the observer and an acceptable process for the terrestrial case must provide for the propagation of the radiation inward through the plasma to the ground instead of outward through the solar corona. Since the critical penetration frequency of the F-region is much higher than the wave frequency of VLF noise, this means that the terrestrial process must produce "extraordinarily" polarized radiation instead of the "ordinary" polarization favored in the solar case.

1.2.1 Selective Traveling-Wave Amplification Process. In a theoretical study of VLF emission by Gallet and Helliwell[5] it was assumed that a part of the low frequency radiation is generated in the earth's exosphere and the selective traveling-wave amplification process in the outer exosphere is postulated. A stream of electrons acts like the beam in a traveling-wave tube and the ambient ionospheric plasma acts like the slow-wave structure. The input signals are assumed to be provided by whistler energy, Cerenkov radiation and thermal radiation. In other words the longitudinal interaction of the electromagnetic wave and a beam of ionized particles would bring about an amplification of the electromagnetic wave provided that the average velocity of the incoming beam is approximately equal to the phase velocity v_{ph} of the electromagnetic waves.

It has been suggested[5] that a discrete well spaced group of charged particles entering the ionosphere may produce down chorus by this process of selective traveling-wave amplification. In a three-dimensional medium this is the same as the Cerenkov process[6]. Using this process Dowden[7] has explained "hiss" as the amplified Cerenkov emission from electron streams.

1.2.2 Cerenkov Radiation. The mechanism of VLF emission by Cerenkov radiation from a charged particle traveling along a geomagnetic line of force has been discussed by various workers[8-13]. Cerenkov radiation is emitted by charged particles when the resolved components of particle velocity equals the phase velocity of the wave in some direction (i.e., the particle velocity matches the component of wave velocity in the direction of particle motion).

For the X-mode the refractive index is

$$n^2 = 1 + \frac{f_o^2}{(f\, f_H \cos\theta - f^2)} \quad , \tag{1}$$

where f_o, f_H and f are plasma, gyro and wave frequency respectively. θ is the propagation angle which is the angle between the direction of wave propagation and the magnetic field line of force. If v represents the particle velocity, for the particle traveling in the direction of the magnetic field ($\varphi = 0$), then the coherence condition for Cerenkov emission is

$$\frac{c^2}{v^2} = n^2 \cos^2\theta \quad , \tag{2}$$

e.g., for the region where $f \ll f_H$ and $f \ll f_o$, substituting Eq. 2 into Eq. 1, one has

$$f = \frac{v^2 f_o^2 \cos\theta}{c^2 f_H} \quad , \tag{3}$$

which suggests that a given frequency may be generated by a Cerenkov process under a wide variety of conditions of particle speed, plasma frequency and magnetic field intensity. The expected electromagnetic power density has been calculated on the basis of incoherent radiation by Ellis[14].

<u>1.2.3</u> <u>Cyclotron</u> (<u>Gyro</u>) <u>Radiation</u>. Cyclotron (gyro) radiation is synchrotron radiation emitted by nonrelativistic particles at the gyro-frequency and its harmonics. The power emitted in the several

harmonics per electron and the polar diagram of emission have been treated extensively in the literature, e.g., Schwinger[15] for the case of a free electron, and Twiss and Roberts[4] for the case of an electron inside an ionized medium. In general, only the fundamental frequency may propagate to the ground without encountering an infinite refractive index at the level where the wave frequency is equal to the gyro-frequency.

The frequency and power emitted from electrons with density N cm^{-3} and velocity v cm/sec in a helical orbit along a magnetic line of force are given by[15]

$$f = \frac{f_H}{1 \pm \beta n \cos \varphi \cos \theta} \tag{4}$$

and

$$P = \frac{8\pi^2}{3} \frac{e^2}{c} f_H^2 \beta^2 N \sin^2 \varphi \tag{5}$$

$$\text{for } \beta^2 \equiv \frac{v^2}{c^2} \ll 1 \quad ,$$

where φ is the angle between the velocity vector of the electron and the magnetic line of force.

An electron trapped between the magnetic mirrors moves following the relation[16]

$$\frac{\sin^2\varphi}{B} = \frac{1}{B_m} \quad , \tag{6}$$

where B is the magnetic flux density and B_m is that at the mirror points. It is noted that the emission power becomes weak around the top of the geomagnetic line of force by the factor $\sin^2\varphi$ in Eq. 5. However, no such examination of radiation power has ever been made.

a. Doppler-Shifted Proton Cyclotron Radiation. The interaction of a traveling-wave-tube-type amplification process requires the velocity matching of the electromagnetic wave and beam over an extensive region of space in order for an appreciable amount of energy to be transferred from the beam to the wave. In order to remove this possible objection, MacArthur[17] has proposed a theory based on a Doppler-shifted proton gyro-concept.

A cloud of protons, impinging on the earth's magnetic field at high speed, will in general be deflected into a helical path about the line of force, rotating with angular frequency $\omega_s = He/Mc$, where M is the proton mass. This rotating cloud of protons may be considered as a source of an electromagnetic wave having an angular source frequency ω_s and moving forward with velocity v. Hence, a Doppler-shift in frequency will result, with the radiated angular frequency given by

$$\omega = \frac{\omega_s}{\left(1 - \frac{v}{v_{ph}}\right)} , \tag{7}$$

where v_{ph} is the phase velocity of the wave, $v_{ph} = c/n$, where n is the index of refraction. For a whistler mode

$$n^2 = 1 + \frac{\omega_p^2}{(\omega\, \omega_H - \omega^2)} , \quad \text{where} \quad \omega_p^2 = \left(\frac{4\pi N e^2}{m_e}\right) .$$

By eliminating n and v_{ph} in the above equations one can solve for the radiated angular frequency in terms of various parameters. MacArthur showed that Gallet's equation for radiated frequency can be derived as a limiting case of a more general equation resulting from a quite different mechanism. It has been pointed out that the Doppler-shifted proton gyro-radiation can be made to cover cases not explained by the TWT method.

Maeda and Kimura[18] have treated theoretically the amplification due to the transverse interaction of the electromagnetic wave with a cyclotron mode of a proton beam in place of an electron beam.

b. Doppler-Shifted Electron Cyclotron Radiation. Dowden[19] has proposed the theory of Doppler-shifted cyclotron radiation from electrons matching the whistler mode in the backward direction to explain "hook" by showing that a discrete bunch of electrons will produce a discrete emission. This theory has been supported with experimentally observed results[20]. Dowden[21] also showed that the cyclotron radiation from a receding electron in the exosphere can be Doppler shifted to a frequency much less than the local gyro-frequency, and a stream of electrons will produce band-limited white noise or "hiss". Associated with the lower frequency limit of the band there is an emission cutoff and the upper limit constitutes a propagation cutoff. It was pointed out[21] that narrow, wide and very wide bands of hiss can be produced by electron streams of even very broad velocity and pitch distribution.

1.2.4 Other Possible Mechanisms Which Have Been Proposed.

a. Plasma Instabilities. It has been shown recently[22] that a beam of solar particles penetrating the ionosphere will eventually excite enhanced plasma oscillations in the lower frequency band and generate an electromagnetic noise which is detectable on the ground. Suppose that at a certain time it is traversed by a homogeneous, incoming electron beam originating from the sun (or from Van Allen belts). The resulting complex medium may be electrically neutral, either if the beam itself also creates positive ions by collision or if ionospheric ions re-establish neutrality. However if the velocity distribution of the electron is strongly distorted in velocity space, a convective instability must automatically occur. This means that if at a certain moment there is a small fluctuation of charge density in the medium, due for instance to a slight local inhomogeneity of the beam, this fluctuation will grow indefinitely while propagating along the beam. Actually its growth will be limited by a nonlinear effect, damping and finally by the disruption of the beam. From the phenomenological point of view the instability will appear as a succession of very rapid variations in place and time of the parameters of the medium such as electron density, current and fields, these variations growing indefinitely while propagating. The onset of nonlinear effects will then change the nature of the disturbance which, instead of remaining purely electrostatic in nature, will acquire radiation properties and generate an enhanced electromagnetic noise. This mechanism is essentially the same as the one proposed by Haeff[23] to explain the origin of solar noise emission. The noise thus generated will eventually reach the ground, either directly with frequencies above the maximum plasma frequency of the underlying ionosphere, or indirectly, by the whistler mode with frequencies below the gyro-frequency, along the geomagnetic line of force. It must be noted that the noise spectrum should correspond to the instability band of the interacting beam-plasma-dispersion diagram, whose frequency ranges from zero to an upper limit somewhat above the electron plasma frequency.

Thus the traveling-wave-tube mechanism to which the VLF emission has been ascribed (Gallet[1]) does not appear to be an essential implication of the phenomenon.

b. Anomalous Doppler Waves from Charged Particles. While studying the ionospheric absorption of the VLF emission at the auroral zone, Ondoh[24] has found that the daytime increases of chorus intensity correspond to daytime increases of incoming particles such as cause ionospheric absorption of cosmic radio noise on quiet days. In view of the fact that the power flux of 3.5×10^{-13} W m^{-2} (C/S)$^{-1}$ cannot be explained by most theories of VLF emission that may explain up to 10^{-15} W m^{-2} (C/S)$^{-1}$ at most, and since the anomalous Doppler waves are known to be growing waves[25], Ondoh has proposed that anomalous Doppler waves from charged particles produce cosmic noise absorption as an origin of VLF emission in the outer exosphere. It was pointed out that it may emit a power of the order of 10^{-13} W m^{-2} (C/S)$^{-1}$.

Ondoh[26] also suggested the possibility of amplification of Cerenkov instabilities in the outer-exosphere at geocentric distances beyond about four earth radii $[2(f_o/f_H)(v/c)]^2 \geq 1$ for a velocity v of the order of 10^4 km/sec. Hence the Cerenkov instability with the complex frequency $f = f_r + i\,\gamma$ may appear in the outer exosphere. The condition for the anomalous Doppler effect is given by Ginzburg[25] as

$$\cos\theta > \frac{c}{nv} \quad . \tag{8}$$

Thus the instability suggested by Ondoh[26] may be the anomalous Doppler effect and therefore the Cerenkov instability may produce the growing wave.

For example, by considering the penetrations of the stream of charged particles with velocities $v_1 = cf_H/2f_o$ and $v_2 > cf_H/2f_o$ into the outer exosphere simultaneously, the VLF emission may be explained since the condition (8) can be met.

1.3 Comments on the Various Mechanisms

The theory of the traveling-wave-tube interaction in VLF emission can be developed further by taking into account some plausible laws of variation of cloud velocities and by explaining the interaction between whistler and VLF emissions by the acceleration of particles by trains of electromagnetic waves.

The TWT mechanism has been considered in great detail for hiss by Dowden[7] in which account is taken of the spiral motion of particles traveling in the magnetic field, the interaction distance for which amplification at any one frequency can occur, and the slowing down of the stream particles by the wave amplification process. It has been shown that narrow band bursts of hiss can be generated by weak electron streams of even very broad velocity and pitch distribution. The center frequency of such a band of hiss is characteristic of the terminating latitude of the line of force of generation.

From consideration of the frequency spectrum it appears[16] that continuous emission such as "hiss" or a multiple of accending tone "chorus" are due to the Cerenkov-type emission and discrete emission "hook" is due to cyclotron emission from electrons traveling away in helical orbits about the geomagnetic field. From the point of view of radiation intensity, on the other hand, if the radiation is incoherent, then both Cerenkov and cyclotron mechanisms are incapable of producing power levels even remotely approaching those observed[18]. For example, the observed intensity of the noise--about 10^{-16} W m^{-2} $(C/S)^{-1}$--is several orders of magnitude greater than would be expected on the basis of Cerenkov emission[14] or gyro-emission by a single particle. This discrepancy is not considered serious, however, since coherent emission by a closely spaced group of particles[27] could increase the intensity to the observed levels. In other words, one way to increase the output from either the Cerenkov or cyclotron process would be to produce some degree of coherence in the radiation from individual particles[28]. This would require that the position of particles in the wave normal direction be such that their radiation components will add in phase. Examination of whistler mode propagation shows that though the longitudinal component of electric field is usually small it may be appreciable if the propagation is sufficiently far from purely longitudinal. As the wave propagates it will tend to trap those particles moving at nearly the same longitudinal velocity; those particles moving slightly slower than the wave will be accelerated, and those moving slightly faster will be decelerated. If this mechanism operates over a substantial length of path, significant changes in the particle velocity distribution may occur, since the velocity of the wave continuously changes with position along the path. In addition the particles will be grouped in bunches of about a half-wavelength, and so the degree of coherence of their radiation will be increased.

Another phasing mechanism, proposed by Brice[29], is based on the resonance between spiralling electrons and whistler-mode waves traveling at the appropriate speed in the opposite direction. In this mechanism the magnetic field of the wave acts to shift the phase of the particle until the force on the electron due to the wave magnetic field is reduced to zero. The result is that the particles are organized in velocity space so that their cyclotron radiation adds in phase in the backward direction.

Advantages of this cyclotron mechanism include strong coupling when propagation is purely longitudinal and the fact that phasing does not require physical bunching of charge.

Observation[30] of VLF noise by the Alouette I Satellite shows that the band of noise shows systematic variation with the position of the space craft in the geomagnetic field; frequency decreases with increase in the latitude of the Satellite. These observations are compared with the theories of generation of VLF exospheric noise (Hiss) developed by Dowden[7,21]. The comparison indicates that the observed spectral distribution of the noise is perhaps more consistent with the Doppler-shifted cyclotron theory of generation, but the dependence on the geomagnetic field is in better agreement with the traveling-wave-tube amplification theory. Although both theories can account for narrow, wide and very wide band noise (neither seems to adequately explain all features of the observational data) it has been pointed out[30] that TWT theory is perhaps the most hopeful and it should receive further study. Thus the efficacy of the traveling-wave mechanism is still open to question.

1.3.1 Periodic Emission and Triggering Hypothesis: (Whistler-Mode Periodic Emission Theory.) A periodic VLF emission can be divided into two types: a dispersive type in which the period between bursts varies systematically with frequency and a nondispersive type in which the period does not vary. In all attempts to explain the periodic VLF emission, authors assume the a priori existence of a small bunch of charged particles that oscillates between mirror points in the earth's magnetic field. It is then assumed that the bunch radiates a noise burst each time it passes through a favorable region of the ionospheric plasma, so that the emission period is the same as the mirror period of the bunch, which is referred to as the "particle-bunch theory of nondispersive VLF emission".

The experimental evidence linking whistlers to both types of periodic emission has been presented by Helliwell[28] and a single, unifying theory of their origin was proposed, which was referred to as "whistler-mode periodic emission theory". From the experimental results it was argued that those two classes of periodic emission are fundamentally the same and that the generation of the emission is controlled by echoing whistler-mode waves, rather than by mirroring particle bunches.

Although the details are not yet understood a mechanism has been proposed[28] in which the whistler waves act to temporarily "organize" the particles in existing, unbunched streams of charge that are trapped in the earth's magnetic field. The individual particles in the organized group then radiate coherently, giving rise to temporary enhancement of the total noise power. It appears that in whistler-mode periodic emission theory, the whistler need only set up the appropriate condition for more effective conversion of kinetic to electromagnetic energy. Helliwell[28] also proposed the experimental test of the triggering theory, and pointed out that on the basis of the triggering hypothesis, the common phenomena "chorus" could be interpreted as the superposition of many sets of periodic emissions traveling on one or more field aligned paths.

It might be of interest to note that recently coherent radiation by plasma oscillation in a laboratory experiment in the microwave range has been reported by Skinner and Vallner[31]. The idea is based on coupling between longitudinal oscillations on the beam and an electromagnetic wave traveling normal to the beam. This observation might be helpful in the study of the VLF emission mechanism by plasma oscillation. The conditions in which coherent generation and amplification of electromagnetic radiation can occur in a plasma have been investigated by a number of authors[4,32,33]. It has been shown that the radiation absorption coefficient may assume a negative value for a particular frequency if there exists a radiative process where this frequency is emitted only by electrons of particular energy, providing that the actual energy distribution of the fast electrons has a positive slope for this value of energy. If the absorption coefficient is negative then a wave traveling through the plasma will be amplified. Bekefi, et al.[32], for example, have shown that even a slight modification to a Maxwell energy distribution can lead to coherent cyclotron radiation.

1.3.2 Triggering of VLF Emission by Transverse Resonance Plasma Instability. An electron injected into a longitudinal magnetic field with some initial transverse motion will rotate at the cyclotron frequency in the transverse plane. If a radio-frequency electric field which is polarized in the transverse plane and which oscillates at the cyclotron frequency is present, a cumulative energy interchange between the electron and the field will occur. This principle of cyclotron resonance interaction has been applied to the construction of a backward-wave oscillator[34] and amplifier which requires no slow-wave circuit. It is interesting to note that in the TWA it is the r-f electric field that does the bunching and the extraction of energy. However, in the case of cyclotron resonance, bunching is provided by the r-f magnetic field and energy extraction is provided by an r-f electric field. A tube of this type will support amplification in both the forward and backward directions. It is well known that if the tube current is high enough backward-wave oscillation will occur, since the feedback mechanism is built in. The backward-wave amplification in the cyclotron resonance interaction may be viewed as a consequence of a plasma instability, which is referred to as "transverse resonance plasma instability". Brice[29] has suggested that this type of instability might be responsible for the triggering of a certain type of observed VLF emission, and Bell and Buneman[35] have carried out development of the theory. The type of instability considered by Bell and Buneman is that due to the resonance between circularly polarized whistler-mode electromagnetic waves propagating in a relatively cold plasma and the gyrating electrons contained in a stream which penetrates this cold plasma.

It was pointed out that both in laboratory plasmas created in a mirror geometry and in the earth's exospheric plasma, such a streaming condition may exist, and ionospheric observation of whistler growth may be expected. For whistler-mode propagation, the wave frequency is always less than the electron gyro-frequency, and for gyro-resonance to occur it is necessary that the wave and the stream travel in opposite directions. Neufeld and Wright[36] consider the process of gyro-resonance in the whistler mode for the case in which the stream has zero initial transverse velocity, and concludes that no instabilities exist for transverse electromagnetic waves propagating along the field lines when the stream direction opposes that of the wave. This conclusion is plausible on the basis of energy considerations (i.e., the stream will fail to transfer energy to the wave). (It should be kept in mind that the situation analyzed by Neufeld et al. would inevitably result in a longitudinal instability.) However, for streams with finite initial transverse velocity, the analysis of Neufeld et al. must be modified and Bell and Buneman have demonstrated that a spread of stream electron velocity in the transverse direction leads to an instability of the stream-plasma system in the whistler mode, with the transverse electron gyration serving as an energy source. Bell et al. showed that an estimate of phase mixing or Landau damping through longitudinal velocity spread indicates that the phase-mixing effect can suppress the electrostatic (longitudinal) instability without suppressing whistler growth. Streams approaching magnetic mirror points can develop high enough gyratory energies to cause whistler excitation, and under typical ionospheric conditions indicating the presence of electron streams, whistler growth rates are calculated that could explain a recent observation of very low frequency emissions. The result of the theory of Bell and Buneman was compared with the observation of the artificial stimulation of ionospheric whistler emissions by ground-based transmitters[37].

The basic approach in the theory of Bell and Buneman involves the examination of a dispersion relation for a general distribution function, using the first-order Boltzmann-Vlasov equation for electrons.

1.4 VLF Emission and Geomagnetic Disturbances

The correlation between the chorus activity and geomagnetic activity has been reported by Storey[38] and Allcock[39]. Storey also found the chorus intensity varying greatly throughout the day. Allcock[39] and Pope[40,41] found the latitude effect on the diurnal maximum of chorus activity. Based on these data, Allcock has shown that the chorus may be generated directly or indirectly by streams or bunches of high-speed charged particles precipitating into the ionized exosphere in the presence of the earth's magnetic field.

Crouchley and Brice[42] and Yoshida[43] found that the average strength or occurrence probabilities of chorus increase with increasing values of the K-index at low latitude stations and show a maximum at moderate values of K-index in the auroral zone.

Ellis[44] has found, from the study of VLF noise of 5 kc/s at Camden, Australia located at a middle geomagnetic latitude of 42°, that all of the noise storms occurred in the main phase of the geomagnetic storm and that half of the noise bursts occurred simultaneously with positive bay. A good correlation has been found by Tokuda[45] between the magnitude of the proceeding bay-type disturbances and the rising time of strength increases of chorus.

Ondoh[46] has found that a close correlation exists between increases of chorus indices continuing for a few hours and geomagnetic pulsation at the auroral zone, using the chorus indices and rapid-run magnetrogram at College, Alaska, during July, 1959 to December, 1960. The result of the observation indicated that the chorus increases may be generated by penetration of high-speed-charged particles into the exosphere, which may also be related to the geomagnetic pulsation.

Dokuchaev[47] has studied the growth of hydro-magnetic waves in a plasma stream moving along lines of force of a uniform external magnetic field through a stationary ionized gas. Both plasmas are assumed to be fully ionized and quasi-neutral. Using a generalized Ohm's Law in the moving and stationary plasmas, hydromagnetic equation of the plasmas, and the Maxwell's equations, Dokuchaev has derived the dispersion equation for plane electromagnetic waves propagating along the lines of magnetic field $\vec{H}$ at very low frequencies ($\omega << \omega_H$, $\omega/k << c$) on the assumption that collisions of electrons with ions are negligible. When $kv_o << \omega_H$, the dispersion equation is given by

$$k^2 = \frac{(\omega - kv_o)^2}{v_{a,s}^2} + \frac{\omega^2}{v_{a,p}^2} , \qquad (9)$$

where v_o is the velocity of the stream, ω the wave frequency, k the wave number, ω_H the gyro-frequency of ions

$$v_{a,p}^{\ 2} \equiv \frac{H^2}{4\pi\rho_p} , \qquad v_{a,s}^{\ 2} \equiv \frac{H^2}{4\pi\rho_s} ,$$

$\rho_{s,p} = (m_e + m_i) N_{s,p}$ the mass density, $m_{e,i}$ the electron and ion mass,

$N_{s,p}$ the number density of the stream and the stationary plasma. Solving for (ω/k) from Eq. 9 yields

$$\frac{\omega}{k} = \frac{v_o \pm v_a \sqrt{\left(\frac{N_p}{N_s}\right)\left(1 - \frac{v_o^2}{v_a^2}\right)}}{1 + \frac{N_p}{N_s}} , \qquad (10)$$

where $v_a^2 = v_{a,s}{}^2 + v_{a,p}{}^2$. Thus if the velocity of the stream exceeds the Alfvén velocity $(v_o > v_a)$, hydromagnetic waves appear in the stationary-plus-streaming plasma system. These waves build up in time.

The chorus increase may be generated by the Cerenkov instability resulting from the interaction of charged particles with the exosphere. When the velocity of an ionized stream exceeds the Alfvén wave velocity, the growing hydromagnetic wave may appear in the stationary-plus-streaming plasma system. The Alfvén velocity in the outer exosphere may be of the order of 10^7 cm/sec. Therefore when the ionized stream with the velocity of 10^8 cm/sec and density of 10 cm^{-3} invades the exosphere along the geomagnetic line of force the growing hydromagnetic wave (10^7 cm/sec) may appear in the exosphere-plus-stream system. These hydromagnetic waves may propagate toward the earth in the stream moving along the geomagnetic line of force and may be observed as the geomagnetic pulsations. Thus the interaction of charged particles or stream penetrating along the geomagnetic lines of force with the exosphere may explain the close relationship between the chorus increase and the geomagnetic pulsation at the auroral zone[48]. The observation of radio noise from auroral electrons in the frequency range of 1 to 7 mc/s has been made by Parthasarathy and Berkey[48]. The emission mechanism is believed to be that of synchrotron radiation from primary electrons spiralling down the magnetic field lines in the auroral zone. It was found that the direction of radiation approximately coincides with the direction of the visual aurora, as determined from the all-sky camera photograph.

1.5 Summary of Research of VLF and ELF Emissions

1.5.1 VLF Emissions--Their Relations with Whistlers and High Energy Particle. The VLF emissions originating in the magnetosphere and the upper ionosphere are of particular interest because of their intimate relation to whistlers and to high-energy particle phenomena in the magnetosphere. It is now considered to be well understood that VLF emissions propagate in the whistler mode, and that they are produced by bunches or streams of high energy particles moving along lines of force in the magnetosphere. In nature and energy these particles do not differ from the Van Allen belt particles or from the intense fluxes of high energy electrons precipitating upon the upper atmosphere that are observed by high altitude balloons. The source of VLF emissions was interpreted, and they were systematically studied in several U. S. laboratories prior to the discovery of these two classes of phenomena (early 1958 for the geomagnetically trapped radiation, and mid 1957 for the precipitation phenomena). A first review of the properties of VLF emissions and the basic mechanism of their production was presented by Gallet at the XIIth U.R.S.I. general assembly held in Boulder, Colorado, September, 1957. It took some time to recognize that these natural radio phenomena and the more or less direct detection of trapped or precipitating particles were different aspects of the same general class of geophysical phenomena.

The relationship between the two fields of observation is far from being obvious and is obscured by many secondary effects, such as the strong variations of the ionospheric absorption for VLF radio signals, and the lack of continuous observations of the particle fluxes at the same place. The more or less steady Van Allen Belt, as pictured from the Satellite observations, does not produce an observed background of continuous VLF emissions, even if the velocity of the individual particles is, from the present theory of the emission mechanisms, largely sufficient to produce the radio emission. The VLF emissions are essentially transient, over a wide range of time scales, and their intensity can be very large compared with the threshold of detectability (typical 10^{-15} to 10^{-14} m^{-2} $(C/S)^{-1}$ compared to 10^{-18} or 10^{-19}). It follows that VLF emissions are more closely associated with transient particle activity in the magnetosphere superposed on the more permanent background revealed by satellites. In addition, the observed VLF emissions (sharp and strong discrete events and hiss, well characterized by their spectra) are not produced by individual particles but are due to the collective effect of excess density particles in bunches or streams.

From the present state of the theory, as well as from the observed periods of certain periodic emissions (the VLF pulsations), one can deduce that, for a large majority of the VLF emissions, the velocities of charged particles required for producing the emissions correspond to electron energies of the order of a few kev. The recent counter results obtained with the Injun I Satellite, equipped to record electrons with energies as low as 1 kev and on a very short time scale, show very large and rapid fluctuations of the particles fluxes, and are in much better agreement with the deductions made from the VLF emission observation than were the earliest measurements.

At the present time it has become clear that VLF emissions are closely related to the dynamics of high energy particle phenomena in the magnetosphere. Unlike whistlers, which are an important propagation phenomena, VLF emissions are characterized by an emission process, producing a well defined narrow band of frequencies due to the passage of relatively few high velocity particles through the ambient plasma. When they are emitted, the electromagnetic waves propagate like whistlers. To understand the shape of the dynamic spectra of VLF emissions it is necessary to take into account the results available from whistler studies of the structure of the magnetosphere.

1.5.2 Trends in the Field of VLF and ELF Emissions Since 1960. Gallet[49] recently pointed out that the trends in studies of VLF and ELF emissions since 1960 are as follows:

1. The separation between the studies of whistler and VLF phenomena have become clear and better understood.

2. The study of VLF emission is no longer pursued by itself and there is a deliberate search for the relationship with high energy particle phenomena. Furthermore, particle physicists are now aware of the importance of these phenomena in their investigations.

3. It has become evident that there is an important relationship between ELF observations and VLF emissions, and that the customary separations were mainly artificial. It has been realized that at least one fraction of the geomagnetic micropulsations have very definite spectra, exhibiting well defined frequencies slowly varying with time and very much like VLF emissions. Also at least a fraction of these geomagnetic micropulsation propagates as progressive hydromagnetic waves through the magnetosphere, or as standing ELF oscillations of parts of the

magnetosphere (such as a particular bundle of lines of force). The detailed mechanism of the production of these hydromagnetic waves is still quite a mystery although they are related to the interaction of solar plasmas with the magnetosphere. It is possible that some well defined ELF frequencies are produced by streams or bunches of particles in a way similar to hydromagnetic waves in the traveling-wave-tube mechanism producing VLF emissions. The term "Hydromagnetic Emission" has been very appropriately used by Tepley[50].

During the same period some new types of studies have been undertaken at a few laboratories. They can be characterized as systematic attempts to relate the individual VLF emission events to other geophysical phenomena and to verify in detail some predicted properties. These studies can be classified in the following ways:

1. Magnetically conjugate point studies.

2. Relationship between VLF emissions and precipitation of high energy electrons upon the low ionosphere.

3. Observation of echoes from sufficiently strong discrete VLF emissions, and establishment that the deformation from one signal to the next is due to the dispersion of electromagnetic waves propagated and reflected exactly like whistlers.

4. Study of repetitive VLF emissions, which present periodically the same spectral shape. These are called "VLF pulsation" or "periodic emission" for convenience.

5. Continuous observations at a network of stations in addition to the ordinary magnetic tape recording of high time resolution, which are necessarily limited to a sampling of two minutes every hour. These

continuous observations of VLF spectra are made by means of a new instrument called a "Hiss Recorder", which deliberately gives a low time resolution in order that one day of data occupies a length of 72 cm on 16-mm film. (Watts, Kock and Gallet[51].)

1.6 Some Propagation Aspects of VLF Noise in the Ionosphere

1.6.1 Landau Damping of Whistlers. In recent years the Landau damping theory has received a great deal of attention. For example, the effect of (close range) collision on Landau damping has been investigated by Platzman and Buchsbaum[52]. Attention has also been directed to cyclotron damping (the analog of Landau damping at cyclotron frequencies) in a collisionless plasma by Stix[53] and Scarf[54].

Scarf[54] investigated the thermal damping of whistlers using the small amplitude solutions to the coupled Boltzmann-Maxwell equations. It was found that the damping is associated with cyclotron resonance for a fraction of the electrons in the magnetosphere, and that the resultant attenuation provides a sharp cutoff at 0.5 to 0.7 of the minimum cyclotron frequency along the path. The correlation of whistler data with the derived complex dispersion relation was used to evaluate electron temperatures at several earth radii; a specific numerical example gave $T \simeq 10^{5\circ}$ K at $R = 4R_E$ (geocentric).

The thermal analysis was applied by Liemohn and Scarf[55] to data supplied by Pope[56], and the most reasonable results for the effective density and temperature at $R/R_E \simeq (4 - 4.5)$ appeared to be $N \simeq (200 - 700)$ electrons per cm^3 and $T \simeq (2.5 \times 10^{5\circ}$ K). In another paper, Liemohn and Scarf[57] examined the thermal attenuation of whistlers, assuming for simplicity of analysis, that the electron component has a velocity distribution of Cauchy form $\sim (v^2 + a^2)^{-3}$, with a being rms value of velocity, which corresponds to an energy dependence of $E^{-2.5}$ when $|v| \gg a$. It was pointed out that the exact shape of the distribution and the concept of temperature are only relevant in the sense that they give the fraction of electrons that participate in the damping interaction at the Doppler-shifted phase velocity. For a total density of 200 electrons per cm^3 at $R \simeq 4R_E$, the thermal attenuation mechanism was found to predict an electron flux of $\sim 4 \times 10^5$ electrons/cm^2 sec ev. for energies near 250 ev. Scarf's small-amplitude theory has been re-examined and amplified by Tidman and Jaggi[58] to include the effect of the fast-particle fluxes.

1.6.2 Radio Wave Scattering by Free Electrons. It is well known that each free electron in an ionized medium containing many free electrons scatters some of the energy associated with a radio wave propagating through the medium. The scatter waves have coherence, limited coherence, or incoherence depending on certain conditions of wavelength and geometry.

Coherent scattering is the standard problem of refraction of radio waves by an ionized medium. Limited coherence, which means that only the scattered waves from limited subvolumes of ionized media are coherent, is the problem popularly known as "ionospheric scatter". Complete incoherence of the waves scattered by free electrons, or simply incoherent scattering, and the conditions under which it is important has been discussed by Gordon[59]. Due to the thermal motion of the electrons, the frequencies of the scattered waves are Doppler-shifted from the incident wave frequency. The width of the spectrum of the scattered signal is therefore a measure of the electron temperature. Free electrons in an ionized medium scatter radio waves incoherently so weakly that the power scattered has previously not been seriously considered. The calculation made by Gordon[59], however, shows that this incoherent scattering, while weak, is detectable with a powerful radar; which thus led him to conclude that the radar, with components each representing the best of the present state of the art, is capable of measuring electron density and electron temperature as a function of height and time at all levels in the earth's ionosphere and to heights of one or more earth's radii.

Associated with the suggestion by Gordon for measurement of electron density in the magnetosphere by radar backscattering above the penetration frequency of the ionosphere, and the successful application of this method by Bowles[60], numerous papers[61-67] have appeared analyzing in detail the theory of this scattering phenomenon. The development of the incoherent backscattering technique for studying the ionosphere and magnetosphere has been perhaps the most important innovation in ionospheric research during the last decade[60].

1.7 Thermal Noise from the Ionosphere

The radio-frequency noise picked up on an antenna originates in various ways. At medium frequencies principal components are man-made noise and atmospherics and the spectrum should also contain a component due to thermal radiation from the ionosphere. Because the ionosphere acts as an absorber of radio waves, it would not be unreasonable to expect that it can also act as an emitter of thermal radio noise. It has been conclusively demonstrated by various workers that thermal emission from the D-region can, under favorable conditions, be observed with a dipole antenna.

The thermal radiation from the ionosphere has been identified and measured by Pawsey et al.[68]. They found that it is in general very weak, corresponding to an effective antenna temperature of about 300°K, or a field strength of about 10^{-9} volt/m in a frequency band of one kc/s under the condition of observation. Their observations led them to suggest a new method for studying the electron temperature in the absorbing (and emitting) part of the ionosphere, which for the frequencies used (2 mc/s), is at a height of about 70 or 80 km. The measured temperature of 240 to 290°K agrees with other observations of temperature at these heights. The argument and method used by Pawsey et al. in an attempt to identify and measure the thermal radiation from the ionosphere are described as follows:

Noise intensities may be expressed in terms of an rms field strength per given bandwidth or in terms of an effective antenna temperature. Pawsey et al. use an effective antenna temperature (in degrees Kelvin) defined as the temperature of "black" walls of a hypothetical enclosure completely surrounding the antenna which, in the frequency band accepted, would give a mean available power at the antenna terminals due to thermal radiation, equal to that actually observed. This mode of specification is quite general and does not presuppose radiation of thermal origin, though it is obviously convenient in discussing such radiation.

The relation between the component of rms field strength in a given direction in a frequency band B, and the equivalent antenna temperature T_a, is derived by equating the available power due to an assumed thermal source to that due to the given field strength E acting on a short-loss free antenna. Thus

$$kT_aB = \left(\frac{Eh}{2}\right)^2 \frac{1}{r_a} , \qquad (11)$$

where k is Boltzmann constant, h is the effective height of the antenna and r_a is its radiation resistance. Since for a Hertzian doublet of length (and hence equivalent height) h, $r_a = 80\,\pi^2\,(h/\lambda)^2$, where λ is wavelength, and for a wavelength of 150 m (f = 2 mc/s), a frequency band of one kc/s and an effective temperature of 300°K, a value commonly occurring in their observation, the r m s field strength is 0.76×10^{-9} volt/m. This field strength is several orders of magnitude below the threshold of sensitivity of most communication receiving systems.

Their observation shows that the natural noise level observed on an antenna at frequencies in the vicinity of 2 mc/s during the hours around noon frequently fall to an intensity corresponding to an equivalent antenna temperature between 200 and 300°K. It is not observed to fall below this, and at the times when this low level is observed the characteristics appear similar to those of thermal noise. Furthermore, there are reasons for believing that this level cannot be accounted for in terms of the integrated effects of great numbers of atmospherics. Thus they argue that these facts are strong evidence for the hypothesis that there is a background source of random noise of this intensity. This background source is identified with thermal radiation from the ionosphere because the measured intensity agrees within the limit of data with that derived from other sources.

This radiation, from a microscopic viewpoint, arises from the acceleration of charged particles due to collisions. Because of the lower mass, electrons radiate very much more effectively than ions so that the contribution from ions should be negligible compared with those from electrons. It was thought that the absorption and emission take place in the ionized atmosphere below the maximum of electron density in the E-region, where the refractive index does not depart appreciably from unity. For a particular direction the contribution to thermal intensity, measured in terms of equivalent temperature, from a small region of thickness Δx at a distance x from the observer, will be given by the product of its electron temperature, T, its emissivity and the attenuation along the path to the observer, $\exp[-\int_0^x K\,dx_1]$, where K is the power absorption coefficient. From the reciprocal law of emission and absorption the emissivity equals $K\Delta x$ (under thermodynamic equilibrium conditions). The equivalent temperature T_e, for this direction is obtained by integrating along the ray and is given by

$$T_e = \int_0^\infty TK \exp\left[-\int_0^x K\,dx_1\right] dx \quad . \tag{12}$$

This can be integrated if T and K are known in terms of x. These can be determined for the given direction if the temperature, electron density N, and collision frequency ν are known functions of height since K is a function of N and ν.

Gardner[69] has made a series of observations of 2 mc/s radio noise over a period of about a year at a very quiet site, with the technique used by Pawsey et al. He reported that the derived ionospheric temperature ranged between about 200 and 250°K and varies appreciably from day to day and is generally lower and less variable in the winter. Using the same technique, Dowden[70] has made a measurement of the temperature of the ionospheric D-region in the auroral zone from observation of 2 mc/s radio noise, and compared this result with measurements made in the temperate region by Pawsey et al. The temperatures of the undisturbed and disturbed ionosphere at the two latitudes are found to be essentially similar.

Little et al.[71] have made the observations of the thermal noise level on a 2.89 mc/s dipole antenna near College, Alaska. They reported that in the absence of cosmic noise and other interference, equivalent midday antenna temperatures during the winter were in the range of 200°K and 250°K which is in good agreement with the temperature of the neutral gas in the lower part of the D-region. Night time observation during aurora indicated that the temperature of the electrons in the lower part of the absorbing region is not markedly affected by the presence of the aurora.

Although, as illustrated in the above, some experimental observations of the thermal noise from the ionosphere have been reported, it appears that no detailed study of the thermal emission mechanism in the ionosphere has ever been done. The thermal radiation has been neglected because its level is exceedingly low, as illustrated by Pawsey et al., and it does not constitute an appreciable source of interference in radio communication. However, the interest in this type of radiation lies in the fact that, if recognized, it can be used to derive information about the temperature of the ionosphere.

II. SOLAR RADIO NOISE

2.1 Sporadic Solar Radio Emission (Radio Bursts): Solar Radio Bursts and Their Characteristics

The great variety of phenomena described as radio bursts is rapidly increasing and it is only with the help of spectral records that a better understanding and classification of these emissions become possible. The characteristics of burst emissions in different frequency ranges differ markedly. Further in the same frequency range burst sources of a different type may be distinguished. The basic observation required to delineate radio frequency bursts comprise dynamic spectra, showing the variation in intensity as a function of both frequency and time; and high resolution studies of the position, size, shape, movement and brightness temperature of the emitting region. For meter-wavelengths extensive results of both kinds have been obtained and fairly well defined classification of source types achieved. In the microwave range (centimeter and decimeter wavelength), on the other hand, most observations have been by means of radiometer of low directivity operating at a single frequency. Hence studies of microwave bursts have been largely "morphological" in character and attempts have been made to find classifications of the burst type on the form of the total power recorded at a single frequency (e.g., Covington[72], Kundu and Haddock[73]), account being taken also of the differences in the total power recorded for opposite polarizations.

From the classical radio spectra of the Australians it was well known that three main types of bursts in the meter wavelength range should be distinguished. For Type I the wavelength remains constant during the existence of the burst. For Type II the wavelength increases slowly and for Type III it increases quickly.

It has been known that large outbursts of solar radio emission from the sun are sometimes followed by periods of prolonged radio "storm" (e.g., Hatanaka and Moriyama[74], Payne-Scott and Little[75]). Until about ten or so years ago these outbursts associated with storms were presumed to be particular cases of "noise storm", which dominate the meter-wavelength radio records of the sun over certain active periods, which are now called Type I storms. The spectral records of Type I storms show that they consist of many narrow-band, short-lived (0.1 ~ 0.2 sec) bursts, suspended on a background of continuous radiation. It also has been known that Type I bursts are associated with a sunspot, and generally are almost completely circularly polarized. The sense of polarization is determined by a magnetic polarity of the preceding spot associated with Type I bursts.

Radio emission from the sun in the form of slow-drift bursts known as "spectral Type II" are characterized by a narrow band of intense radiation that drifts toward lower frequencies at the rate of up to 1 mc/s and a duration of the order of minutes[76]. Type II bursts often show fine structures, frequency splitting and herringbone structure. In 60 percent of the cases, a fundamental and a second harmonic band have been observed, often of the same order of intensity, while the third harmonic was invisible. The work of Roberts[76] and Thompson[77] shows that these are the bursts that produce magnetic storms on earth.

Bursts of spectral Type III, which on many days dominate the record of solar activity in the meter wavelength spectrum, are recognized by the rapid drift of the frequency of maximum intensity from high to low frequency (Wild and McCready)[78]. Type III bursts are always associated with flares, often small flares, and more especially with those showing sudden puffs or dark marking that move away from the flare.

Next to the three "classical" types of bursts, newer Types IV and V have been studied by various workers (Boischot[79], McLean[80], Wild and his associates[81-83]).

While observing the sun with a multi-element interferometer of 169 mc/s, Boischot has made a distinction between ordinary noise storm (Type I) and storm, in which he gives the new definition of Type IV bursts. The Type IV burst is an emission extending through the meter, decimeter and centimeter wavelengths of continuous radiation, with low frequency cutoff, mostly following a strong flare with a Type II burst. It develops smoothly, reaches a maximum after 20 to 40 minutes and may last from one to three hours. Since the Type IV bursts are very complicated phenomena, the resolution of various components is not as yet completely known. However, it has been suggested that the resolution of three major components IVm, IVdm and IVμ would be useful for the time being[84]. Some characteristics observed by Takakura of the Type IV bursts are as follows[85]:

1. The intensity spectra of Type IV bursts have generally three maxima corresponding to three components, IVm, IVdm and IVμ. The histogram for the center frequencies have three maxima, 70-100 mc/s for Type IVm, 300-500 mc/s for Type IVdm and above 9000 mc/s for Type IVμ.

2. The bandwidth of Type IVm bursts is almost constant irrespective of both the position of the radio source and the intensity of the bursts. Therefore, the radio sources of this type seem to be optically thin for radio emission.

3. Owing to a directivity of the emission itself, or owing to a propagation effect, the intensities of Type IVm bursts and Type IVdm bursts decrease at about the limb of the sun by a factor of 0.1 and 0.3 respectively. Type IVμ bursts are almost nondirective.

4. Some of the Type IVm bursts show frequency drift from high to low at the rate of 30-40 mc/s per minute.

Type V is also a continuum emission extending over a very broad band, but here the centimeter wavelength is particularly enhanced. It is much shorter and stronger than Type IV and generally follows a Type III burst. The comparison of the characteristics of various types of radio bursts has been given by Denisse[86].

2.2 Mechanism of Generation of Solar Radio Bursts

The earlier spectral observation of Type II and III bursts showed that the frequency drift could be interpreted as a fast outward movement of a disturbance through the solar corona. This interpretation is based on a "plasma hypothesis", namely that the radio emission was due to plasma oscillations excited in the coronal gas surrounding a suitable kind of localized disturbance. Since the plasma frequency decreases with height in the Solar corona, the observed drift from high to low frequencies corresponds to an outward movement of the disturbance. This interpretation was not taken particularly seriously until subsequent observation revealed that in some Type III bursts the source radiated in two bands corresponding to a fundamental frequency and its second harmonic; this strongly suggested that plasma oscillation was responsible[87].

On the other hand, Wild, Sheridan and Trent[83] working with a two-element, swept-frequency interferometer have observed that the motion of the Type IV sources cover a range of frequencies, and they reported that, at any one time, all frequencies arrived from the same direction (with a little scatter). This observation was taken as evidence that the mechanism of emission is not plasma oscillation, since radiation emitted from plasma oscillations will be restricted to frequencies near the fundamental (and second harmonic) of the plasma frequency in the region of the source and so a wide range of frequencies cannot be emitted from the same point.

In the following the origins of various types of solar radio bursts which have been postulated with be reviewed.

Type I Bursts:

Two possibilities have been suggested.

a. Plasma Oscillation. Perhaps shock-magneto hydrodynamical waves play the role of the exciting agent (Ginzburg and Zehelzniakov[88]).

An attempt has been made by Sen[89] to explain the excitation of a plasma wave by instability of the shock wave front, but it was considered by Ginzburg et al.[88] to be groundless.

b. Magneto-Bremsstrahlung (Synchrotron) Radiation. Takakura[90] has assumed that Type I bursts are caused by synchrotron radiation of electron packets (a size of every packet $\ell < \lambda$). The electron of every such packet gives the coherent radiation, but a total radiation of the whole system consists of the radiation of separate packets (i.e., the electron phase in different packets has a random distribution). Ginzburg et al.[88], however, have shown that bursts of Type I by synchrotron radiation of electrons is not likely because there is no reason to assume that emitting particles can considerably change their energy in a time ≤ 1 sec (characteristic of the burst Type I).

Kai[91] has deduced the following features from the data taken with an interferometer and polarimeter at 200 mc/s at the Tokyo Astronomical Observatory:

a. The radiation at the source must contain the ordinary component of about the same amount as the extraordinary component. (At the extreme limb the burst is nearly unpolarized.) From the center-limb variation in polarization it is thought that the polarization of the received radiation is due to the differential absorption of two modes of waves along the path, but not due to the polarization at the source.

b. Very strong radiation must be emitted effectively in a small frequency range. (Center-limb variation in intensity of burst.)

c. Considerably strong directivity. Whether it is due to the mechanism of generation or to the effect of the propagation is not clear. Probably the magnetic field may play an essential role in the generation of burst. The radiation might be emitted from the plasma oscillation which is coupled with the magnetic field.

Type II Bursts:

Emission is due to plasma oscillation in the solar corona; the drift rate of Type II bursts corresponds to an outward velocity of 1000 to 1500 km/sec. It is thought that the primary agency with this velocity[76,92] is a shock wave, e.g., the plasma oscillation could be excited by the passage of a shock front ahead of a fast moving column of gas (Westfold[93]).

It is possible that electrons running through the shock wave front directly generate the transverse electromagnetic wave that is seen as the Type II bursts (Tidmann[94]). But the shock wave may act in the same way to accelerate particles until they radiate Cerenkov plasma waves that scatter off density irregularities (possibly the shock front itself).

Type III Bursts--(Plasma Oscillation):

The drift rate of Type III bursts corresponds to an outward velocity of 1/4 to 1/2c, where c is the velocity of light[95]. The primary agency with those velocities must surely be a stream of charge particles.

A two-step process[33,96-10] is regarded as generating the radio waves:

a. The particles excite a longitudinal plasma wave by Cerenkov radiation.

b. The plasma waves are partially converted into transverse waves which can propagate freely to the earth by scattering on inhomogeneities in the electron density.

Type IV Bursts:

Boischot[79] suggested that synchrotron radiation from relativistic electrons spiralling in a magnetic field was the cause of this type of burst. It is to be noted that Wild's observations[83] are consistent with this suggestion.

Types II and III have received considerable attention in the past. Because the theory of the shock wave and its interaction with plasma is very complicated and incomplete, the theory of the Type II burst is less developed. An attempt has been made by Ginzburg and Zhelezniakov[88] to compare different mechanisms of sporadic radio emission and to show the relation between them.

2.3 Explanation of Some Observed Characteristics of Radio Bursts

2.3.1 Type II Bursts.

a. Harmonics. Most Type II bursts have a second harmonic but not third or higher-order harmonics. Roberts[76] suggested that the observed intensity ratio may be explained most directly by assuming that they are generated by a nonlinear oscillation of the plasma with the limitation that the oscillation is not sufficiently nonlinear to radiate an appreciable third harmonic.

Smerd[101] considered the traveling-wave solution of nonlinear longitudinal electron oscillation in a plasma stream in the absence of a magnetic field. He suggested that if large oscillations of this kind were responsible for the solar radio bursts, the bursts should be rich in harmonics, and the amplitude of the third and fourth harmonics might be considerable. Maxwell and Thompson[92] pointed out, however, that longitudinal oscillation of the plasma in the absence of a magnetic field would give virtually no radio-frequency emission.

Krook (unpublished) suggested the explanation along the following lines[92]. Although the large amplitude instantaneous disturbance may be analyzed into a superposition of periodic waves of various modes and frequencies, the propagation of the disturbance involves extremely complex coupling between the various modes and various frequencies. One can, however, use the superposition picture in the following restricted way. Supposing the behavior of those transverse components of the instantaneous disturbance correspond to the local plasma frequency and its harmonics, some fraction of the energy in the wave at the local plasma frequency will escape because of the outward motion of the disturbance through a medium of decreasing density. The second and higher harmonics, however, are only weakly coupled with the medium and can easily escape from the region of the disturbance. If energy were not being transferred continuously from the disturbances into those higher harmonics, they would appear only as initial transients. However, the depletion of the second and higher harmonics is counteracted by nonlinear interaction, which continuously transfers the energy into them. The precise character of the radio-frequency emission depends intimately on the nature of the nonlinear transfer mechanisms.

Sturrock[102] studied the interaction between longitudinal (electrostatic) and transverse (electromagnetic) waves in a plasma and showed that in a uniform plasma in the absence of magnetic fields the dominant interaction couples two longitudinal waves with one transverse wave. Hence one would anticipate that the dominant nonlinear mechanism for radiation from an excited plasma leads to emission at twice the plasma frequency. His calculation indicated why generation at the second harmonic should be stronger than that at any higher harmonic. A nonlinear effect will give rise to radiation at the fundamental only at an order higher than that giving rise to radiation at the second harmonic. However, inhomogeneities of the plasma or a magnetic field would promote coupling between longitudinal and transverse modes at the fundamental frequency, giving rise to radiation. The result given by Sturrock seemed to explain why emission is observed predominantly at the fundmental and at the second harmonic.

Cohen[103] has pointed out that the characteristics of Type II bursts can be readily explained by the two-step process, as for the Type III bursts. (See Ginzburg[33].) A different possibility[94] is that the density ratio across the fast shock wave is four and therefore the plasma frequencies just ahead of and just behind the shock wave differ by a factor of two. These two plasma frequencies could be excited essentially simultaneously by fast particles.

b. Splitting Structure. Many Type II bursts show a splitting structure, i.e., both fundamental and second harmonic bands are split into two bands each with separation of the order of 10 mc/s. Various attempts to explain this splitting have been made, generally based on a position of zeros and singularities of the magneto-ionic dispersion equation. Cohen[103] also pointed out that the most plausible suggestion[104] is that the two frequncies correspond to the extraordinary mode singularity for $\theta = 0$ and $\theta = \pi/2$. Waves are generated near these singularities by Cerenkov radiation. The waves correspond closely to plasma waves, and they might be converted into the magneto-ionic modes that can escape to the earth by scattering on the ion component of thermal density fluctuations.

2.3.2 Type III Bursts.

a. Harmonics. The Type III bursts often have a second harmonic. The Cerenkov spectrum[97], however, is concentrated just above the local plasma frequency, so the second harmonic is not generated directly, but rather comes from the second step, the scattering process. The density inhomogeneities responsible for this frequency doubling must themselves be plasma waves. This is called "combination scattering"[33]. Thermal fluctuations excite plasma waves, but it is very difficult to obtain the required intensity of a second harmonic (as intense as the fundamental) by thermal excitation alone. It appears as though this scattering and generation of the second harmonic resulted when the Cerenkov plasma wave scatters off their cousins, the wave which has been generated a moment before by some preceding particles. There will be a continued overtaking and scattering of one wave by another because the Cerenkov spectrum is distributed both in angle and in frequency, and each component has its own group velocity. The fundamental of Type III bursts may be obtained by scattering of the Cerenkov plasma wave on the ion component of thermal density fluctuation[33,98]. This component consists of damped ion waves and has a spectrum of its own, so that the Type III spectrum is the convolution of the Cerenkov spectrum and the fluctuation spectrum[98].

b. Radiation Intensity. The radiation intensity of Type III bursts depends on the number of particles within the Debye sphere as well as on the type of radiation process, namely either coherent or incoherent. Radiation intensity has been calculated by Ginzburg[33] for the case of many particles per Debye sphere which is a two-fluid situation, with the plasma waves generated by a two-stream instability limited by nonlinearity. In a certain velocity range, the Cerenkov waves interact with the particles of the beams, and this results in a coherent bunching of the electrons. This bunching, which is a manifestation of the double-beam instability, occurs at velocities for which $f'(v) > 0$, where $f(v)$ is the usual velocity distribution function and produces a greatly enhanced rate of conversion of kinetic energy to electron oscillation. On the other hand, for the case of one particle per Debye sphere, which is the independent particle situation, the radiation intensity has been derived by Cohen[97], with the plasma wave generated by incoherent Cerenkov emission. However, the theory for the intermediate case, where the particles may be radiating partially coherently, has not been worked out yet.

c. Duration, Drift Rate and Bandwidth. The duration of Type III bursts can be related to the electron-proton collision time. If the electron waves associated with the Type III bursts are excited by the double-beam instability, the small natural bandwidth of the wave results in a time constant of Landau damping that is always negligible compared with the collision frequency. Moreover, electron scattering is apparently more important than Landau damping for establishing a minimum drift rate. The bandwidth of bursts should be determined by the radial extent of the exciting agent and by thermal density fluctuation in the corona.

In a nonmagnetic plasma the primary mechanisms responsible for converting longitudinal electron waves into transverse electromagnetic waves are Rayleigh scattering and combination scattering[33].

Rayleigh scattering produces no change in frequency and therefore plays no role in determining the bandwidth of the escaping radiation. Combination scattering, on the other hand, involves the scattering of the excited waves by electron waves carried by the electron density fluctuation of the medium, and the bandwidth of the scattering wave will be approximately the sum of the bandwidths of the two waves[99].

A systematic theoretical study of the mechanisms of sporadic solar radio emission has been made by Ginzburg and Zehelzniakov[88] by considering radiation in isotropic and magnetoactive plasmas for coherent as well as incoherent types. They pointed out that, generally speaking, the stream of charged particles moving in the magnetoactive plasma is unstable and will bring about the coherent radiation of ordinary and extraordinary waves, when a longitudinal electric field exists in these waves, which causes grouping of radiating particles. They also indicated that a further development in their theory is needed along the following lines:

1. To determine the polarization of the magneto-Bremsstrahlung high-level radiation above the spot.

2. To find the mechanism of excitation of plasma oscillation leading to the appearance of Type I bursts.

3. To take more completely into account the reabsorption for the incoherent radiation.

4. To find the generation mechanism of the Type II bursts by the streams of slow particles.

5. To consider the stable nonlinear plasma oscillation in order to determine the intensities of harmonics.

It appears that the details of the generation of the radio waves from the sun and their subsequent propagation through the solar atmosphere to the earth are not at all clear yet, but nonlinear and particle-wave interaction phenomena are certainly involved.

2.4 Some Concepts of Electron Tube Theory and Electro-Magneto-Ionic Waves in the Study of Solar Radio Noise

2.4.1 Space-Charge-Wave Amplification Effect. Space-charge-wave amplification in the moving interacting charged beams has been used in an electron wave tube[105-107] to explain the abnormal intensity of solar radio outbursts[23,101,108,109]. A mechanism of generation of radio energy, which is believed to be responsible for the observed anomalous solar noise has been presented by Haeff[23] to interpret the observed data on the intensity of solar radiation and its spectral distribution. The observed anomalous r-f radiation from the sun is associated with sun-spot activity and is believed to be generated within intermingling streams of charged particles issuing from the active area of the sun. Such streams are known to have the property of greatly amplifying initial space-charge fluctuation over a range of frequencies determined by the density and velocity distribution of the particle in the stream. Haeff has reviewed the theory of generation of radio energy resulting from space-charge interaction between streams of charged particles and applied to the solution of solar radio noise problems. The space-charge-wave interaction in streams of charged particles results, under certain conditions, in imparting to the space occupied by the streams, the characteristic of a medium having negative attenuation. This means that under such a condition an initial perturbation which exists in the stream (such as caused by statistical fluctuation, e.g.) will be amplified in an exponential manner as the disturbance propagates along the stream. The amplification process continues until the available energy is exhausted. This energy is derived from the kinetic energy of the particles in the stream so that the energy spectrum of the composite electron cloud will be substantially modified after a prolonged coexistence of the streams of different energy. The kinetic energy is thus partially transferred into the energy of the electromagnetic fields associated with space-charge waves and can be observed as radiation emanating from the streams of charged particles.

The method of analysis employed by Haeff is that of the linearized (small perturbation) one-dimensional, single-velocity one. He considered first-order perturbations of the form $V = V_o \exp(\Gamma z + j\omega t)$, where Γ is the complex propagation constant corresponding to a frequency ω, in a medium composed of k streams of particles, each of charge e and mass m, of which the typical nth component stream has a particle density ρ_n and velocity v_n. He stated that Γ is determined by the following (dispersion equations):

$$\sum_{n=1}^{k} \frac{\omega_n^2}{(\omega + j\Gamma v_n)^2} = 1 \quad , \tag{13}$$

where

$$\omega_n^2 = \frac{e\rho_n}{m\epsilon_o} \quad .$$

In this way, for the special case $k = 2$, and $\omega^1 = \omega^2$, he found that the spatial amplification occurs over a limited range of values of the factor $\omega(v^1 - v^2)/\omega^1(v^1 + v^2)$. It is noted that this is essentially the mechanism of "double-beam instability", which is well known. Haeff also pointed out that the frequency of disturbance which can be amplified by the space-charge interaction within inhomogeneous clouds does not have to be near the plasma frequency as has always been assumed by previous investigators.

Because of rather good agreement shown between the theoretical results and the observed data, a more detailed analysis of abnormal solar radiation on the basis of Haeff's theory appeared to be profitable.

Although Haeff's simplified single-velocity theory does indicate the nature of the processes, its application to the solar atmosphere has been questioned since there the thermal velocities are of the order of most injected beam velocities or greater. Feinstein and Sen[108] have re-examined and extended the two-beam case of Haeff's theory and discussed the modification introduced by an appropriate model of thermal motion. They took into account the effect of thermal velocities by utilizing an approximation to a Maxwellian distribution, and found that the possibility of growth exists even for a beam injected velocity much smaller than the mean thermal velocity in the region and narrow bandwidths are encountered under these circumstances.

The possibility of accounting for much of the abnormal radio noise received from the sun on the basis of conversion of the kinetic energy of ejected prominent material into electromagnetic radiation has led several workers to consider the existence of plasma oscillation by moving charge particles.

The mechanism of conversion of the longitudinal oscillation into transverse electromagnetic energy has been studied by various workers, e.g., Ginzburg and Zhelezniakov[88] by scattering process, and Feinstein and Sen[108], and Feinstein[109] with the electron tube interaction model. When one considers the means utilized for the conversion of the energy of longitudinal space-charge waves into transverse electromagnetic oscillation in many types of electron tubes, one notes that the cavity entered by the bunched beam is designed to produce a large electric field in the region traversed by the beam for a relatively low energy storage, at the frequency of the space-charge wave. The wavelength of the two oscillations will generally be quite different under these conditions, but this does not effect the energy transfer because the interaction is confined to a region which is small compared to either wavelength. It is this independence of the wavelength of two modes which makes it possible for each to satisfy its own dispersion relation. When the region of interaction is extended over many wavelengths, on the other hand, a match is required both in frequency and in wavelengths in order for net interchange of energy to occur. For such a double matching to be in agreement with the dispersion relation for the two modes (which is a very special circumstance) there will normally be no excitation of the transverse mode. An exception arises if a region exists in which the wave characteristic varies considerably within a wavelength, or a period. The electron tube interaction model or its temporal equivalent then becomes applicable since the rapidly varying condition permits a net energy delivery with only one of the parameters of the two modes matched. Such a situation can arise if steep gradients are present in the medium characteristic as might occur near the edge of prominence eruptions, or if the rate of growth of the longitudinal oscillation is such as to cause a considerable departure from uniformity in the amplitude of these oscillations within a wavelength spatially, or a period temporally. Feinstein and Sen suggested that since the usual calculated growth is very rapid, this last state of affairs may well provide the answer.

A quantitative investigation of energy transfer under these conditions requires a nonlinear theory.

The nonlinear theory of space-charge waves in moving interacting electron beams has been studied by Sen[110]. He considered the complete equation of interaction (without the linear approximation) of two moving, one-dimensional, single-velocity electron beams of given densities (with sufficient number of ions to make the charges macroscopically neutral). This analysis showed that the propagation of a steady-state space-charge wave is possible in such a medium. The period of the space-charge wave is a function of its amplitude and phase velocity. For small amplitude the oscillation is a simple harmonic, and the characteristic dispersion equation[23] of the first-order theory is obtained. For a given phase velocity of the wave, the oscillation becomes increasingly anharmonic with increase of amplitude. Beyond a particular value of the amplitude (which is a function of the phase velocity of the wave), the wave form of the oscillation becomes discontinuous. This theory then was applied[110] to estimate the relative intensity of the second harmonic component in solar radio bursts, discovered by Wild and his co-worker[81]. A theoretical analysis based on the antenna theory of electromagnetic radiation from an oscillating plasma gives a radio flux of the order of magnitude of that observed. Sen also pointed out that this analysis can be extended to n-beams and to the continuous velocity distribution situation. One of the essential steps in this analysis is the derivation of nonlinear dispersion relations; for the two-beam case this derivation can be made with the help of an equation of motion, a continuity equation and a Poisson equation. Bohm and Gross[111] have derived it for the case with a continuous velocity distribution. Sen has given a derivation of the nonlinear dispersion relation by the Boltzmann equation[110].

Wild and his co-worker[81] have reported observing a fundamental and its harmonics in the radio spectrum of some solar disturbances. Three characteristic features of the observation are as follows:

1. The frequency band drifts toward the lower frequencies with time.

2. The received intensities of the fundamental and second harmonic are similar.

3. The harmonic peak usually occurs at slightly less than twice the frequency of the fundamental peak.

The presence of the second harmonic implies a nonlinear oscillator and suggests a longitudinal plasma oscillation.

Smerd[101] has shown that exact traveling-wave solutions, rich in even harmonics, can be obtained for a nonlinear plasma oscillation. He considered the case of a longitudinal electron oscillation in a plasma stream, with the effects of temperature and magnetic field neglected. His analysis showed that, if large oscillations of this kind are responsible for the emission of solar radio bursts, his result would suggest that harmonics higher than the second may yet be discovered.

The space-charge-wave amplification mechanism may be compared with two other mechanisms of plane-wave amplification which were published earlier by Pierce[105] and Baily[112].

2.4.2 Plane Wave-Amplification. In Pierce's theory of fluctuations in a stream of electrons, he considers the perturbations which can arise through the presence of a second stream of charged particles, namely positive ions, and obtain an equation for determining Γ which is formally very similar to Eq. 13. This theory yields plane wave amplification even when the stream velocity of the positive ions was neglected.

Baily's theory of spontaneous waves in discharge tubes and in the solar and other atmospherics is based on the general investigation of a plane wave in an ionized gas, which is pervaded by static electric and magnetic fields $\vec{E}_0$ and $\vec{H}_0$ respectively. Baily pointed out that, in general, over several ranges of frequency, the ionized medium acts as an amplifier for one or more of the eight possible type waves, of a given (real) frequency, which can travel through it, and that through this mode of wave amplification almost any initial random fluctuation can grow into electric noise. Baily further showed that the presence of a static electric field was found to be essential and that of a static magnetic field to be favorable to such amplification. The fundamental equation of Baily's theory (when the vibration of the positive ions are neglected*) is given as follows[113].

The complex wave number $\ell(\equiv j\Gamma)$ is related to ω by a dispersion equation equivalent to

$$X(Y^2 - \Omega_1^2 Z^2) + U_T^2 \ell^2 [Y(R - i\nu) - \Omega_1^2 Z] - RY\Omega_T^2 Z - 2\ell RZ\Omega_1(\vec{\Omega}_T \cdot \vec{U}_T) = 0 \quad , \qquad (14)$$

where $X = R^2 - \tau\ell^2 - 1 - i\nu R$,

$Y = RX + R - i\nu Z$,

$Z = \ell^2 - \omega^2$,

$R = \omega - U_1\ell$,

$\vec{U}$ = the mean drift velocity of the electrons,

$\vec{\Omega}_0 = - e\vec{H}_0/mc$ (using Gaussian unit),

ν = the collision frequency of an electron with molecules and

τ = one third of the mean square velocity of agitation of the electrons.

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* The more complete theory, including the motion of the positive ions, has been given by Baily[114] also.

The subscript l and T, respectively, denote components along and transverse to the positive z-direction (oz), the direction of wave propagation and the units of velocity $\vec{U}$ and frequency ω are taken as equal, respectively to c, the velocity of light and p, the electron plasma frequency. It can be deduced from Eq. 14 that, when ν is not too large, wave-amplification exists in certain frequency-bands under any one of the following three simple conditions:

1. $\vec{U}$ and $\vec{H}_0$ are parallel to oz and $\tau = 0$.
2. $\vec{U}$ is oblique to oz, $\vec{H}_0 = 0$ and $\tau = 0$.
3. $\vec{U}$ is parallel to oz, $\tau > U^2$ (approx.) and $\vec{H}_0 = 0$.

These offer simple examples of wave-amplification occurring (in Haeff's phrasing) "without the presence of any field-supporting resonator or wave-guiding structures". Moreover, in some of these examples there is an associated Poynting flux.

Thus it appears that in order to explain solar and other electric noise it is not necessary to postulate (with Haeff) interaction of two or more different components of streams. It is, however, important to note that the superposition, on a single stream of charged particles, of other streams or of a static magnetic field or of random motion of the particles--each and all increase the existing capacity of the medium to amplify plane waves.

2.4.3 Electromagneto-Ionic Waves in a Magnetized Ionized Region.

It has been shown by Baily[112] that the nonrelativistic theory of plasma waves in an ionized gas pervaded by static electric and magnetic fields was found to offer a simple explanation of the spontaneous generation of strong high-frequency noise in a discharge tube subjected to magnetic field and in a sunspot. In order to examine the generation of solar noise under the condition in which the electrons attain drift velocities approaching that of light, it becomes necessary to consider the relativistic effect[115,116]. The relativistic theory of electro-magneto-ionic waves has been developed by Baily[117] and the need for such a development was reinforced by the fact, independently pointed out by Walker[116], that in the absence of magnetic fields and electron temperatures the non-relativistic theory may incorrectly lead to certain wave amplification. Baily showed[117] that in the absence of static magnetic field with the effect of collisions neglected, either in ionized gas or in interpenetrating double streams of electrons, certain waves propagated obliquely to the drift motion may both grow and possess Poynting fluxes. These fluxes are such that certain initial disturbances can lead to the escape of amplified electromagnetic energy from an ionized medium. The exchange of momentum and energy, between the streams of electrons and ions and the growing waves, is discussed by means of the momentum-energy tensor of the charged particle and of the electromagnetic field.

Baily's theory is based on the following laws:

I. Maxwell's law for electromagnetic fields.

II. The conservation of electron and positive ions.

III. Maxwell's law of the transfer of momentum in a mixture of different kinds of particles.

The result of this theory[117] shows that both theory and observation lend support to the hypothesis which Baily suggested[112] previously that a notable part of cosmic noise and strong solar noise originates as electromagneto-ionic waves in magnetized ionized regions.

III. SUMMARY

Radio noise in the ionosphere may be classified into two categories--thermal and nonthermal.

During recent years a great deal of attention has been paid to the study of VLF emissions (nonthermal), specifically with regard to mechanisms of generation as well as its relationship with whistler and with other geomagnetic phenomena. Although various mechanisms of generation have been advanced to date in an attempt to explain the VLF emission, it appears that no one particular mechanism is capable of explaining all features of VLF emission observations, i.e., some types of mechanism appear to be more convenient than others to explain certain types of VLF emission.

Most analyses appearing in the literature primarily deal with the dynamic curve (frequency-time characteristic) of VLF emissions, and no attempt seems to have been made to consider the aspect of radiation intensity. Furthermore linear analyses appear to dominate the existing publications on the subject. It will be of value to study the radiation intensity (power spectrum) which would most likely involve the energy transfer of various kinds as well as the motion of charged particles and would require a nonlinear analysis in order to obtain reasonable results.

In contrast to the VLF emission, the thermal radiation (thermal noise) from the ionosphere has received very little attention. The main reasons for this neglect appear to be due to the fact that, on one hand, the thermal noise level measured on an antenna is usally exceedingly low and it does not constitute an appreciable source of interference in radio communication. On the other hand, the researchers in the field of ionospheric phenomena seem to be more interested in and busy with the study of nonthermal processes such as VLF emissions, whistlers and ELF emission, which lie in the frequency range up to 30 kc/s.

However, it must be pointed out that this type of radiation belongs to a general subject of noise radiated from a plasma, which is of great interest, and if the spectral distribution of the emitted energy is characteristic of the plasma properties, a measurement of radiation provides specific information on the plasma. As an example, knowledge of the radiated power gives a measurement of the electron temperature in the plasma, and this has been used as a powerful diagnostic technique. For a plasma in a steady state, macroscopic radiative transfer concepts without detailed knowledge of atomic processes can be applied and emission spectra determined from the electromagnetic wave absorption, transmission and reflection properties of the plasma. These determinations are complicated by the nonuniformity and geometrical configuration of the emitting plasma.

The survey of the literature indicates that some experimental observations and measurements of the thermal radiation (noise) from the ionosphere have been made by few workers with a linear antenna operating in the vicinity of 2 mc/s, and the electron temperature in the D-region of ionosphere has been derived using a simple analysis based on macroscopic concepts. However, it appears that no literature is to be found which undertakes a detailed rigorus study of the thermal emission in the ionosphere from a microscopic point of view. In order to obtain a good understanding of the fundamental process involved in the thermal emission, it will not be unreasonable to expect that the study of motion of electrons, under a general physical condition, will be required in which the general Boltzmann transport equation will enter into the analysis. The publications dealing with some effects of electron thermal motion in the ionosphere have appeared in connection with the studies of Landau damping of whistlers, as well as in the study of radio wave scattering in the ionosphere and magnetosphere.

In reviewing the subject of solar radio noise, particular attention was paid to the mechanism of generation of various types of solar radio bursts. It appears that, similar to the case of radio noise in the ionosphere, various mechanisms have been proposed for various types of solar radio bursts, and some mechanisms seem to be more convincing than others. The mechanisms postulated so far are quite similar to those advanced for the nonthermal emission in the ionosphere. Although the synchrotron radiation from relativistic charge particles seems to play an important role, it appears that the majority of solar radio bursts can be explained by the radiation from plasma oscillation which can be induced by various means, e.g., by corpuscular stream or by shock wave.

The space-charge-wave amplification effect (double-stream instability), which was developed originally in the electron tube theory, has been applied to the study of solar radio noise emission by various workers.

Although some nonlinear analyses in this connection have appeared in the literature, most publications considered a simple single velocity beam model in the beam-plasma system.

This review leads us to believe that there are still many areas of study on the subject of radio noise requiring investigation. In view of the fact that we are interested in the application of the nonlinear microwave tube interaction theories to ionospheric processes and other related phenomena, there are few areas which seem to be particularly interesting.

They are listed as follows:

1. Selective traveling-wave amplification process.
2. Transverse instability. (Plasma instability in the whistler mode caused by a gyrating electron stream.) "Cyclotron resonance backward-wave oscillator-concept".
3. Thermal radiation from the ionosphere.
4. Landau damping of whistlers.
5. Radio wave scattering by free electrons.
6. Scatter from man-made irregularities in the ionosphere D-region.
7. Beam-plasma interaction. (Radiation from plasma oscillation.)
8. Space-charge-wave amplification process. (Double-beam instabilities.)

LIST OF REFERENCES

1. Gallet, R. M., "The Very Low-Frequency Emissions Generated in the Earth's Exosphere", *Proc. IRE*, vol. 47., pp. 211-231; February, 1959.

2. Helliwell, R. A. and Morgan, M. G., "Atmospheric Whistlers", *Proc. IRE*, vol. 47, pp. 200-208; February, 1959.

3. Marshall, L., "Production of the Sun's Non-Thermal Radio Emission by Čerenkov Radiation", *Astrophys. Jour.*, vol. 124, pp. 469-475; September, 1956.

4. Twiss, R. Q. and Roberts, J. A., "Electromagnetic Radiation from Electrons Rotating in an Ionized Medium under the Action of a Uniform Magnetic Field", *Australian Jour. Phys.*, vol. 11, pp. 424-444; September, 1958.

5. Gallet, R. M. and Helliwell, R. A., "Origin of Very Low Frequency Emissions", *Jour. Res. NBS.*, vol. 63D, No. 1, pp. 21-27; July-August, 1959.

6. Pierce, J. R., "Interaction of Moving Charges with Wave Circuits", *Jour. Appl. Phys.*, vol. 26, pp. 627-638; May, 1955.

7. Dowden, R. L., "Theory of Generation of Exospheric Very-Low-Frequency Noise. (Hiss)", *Jour. Geophys. Res.*, vol. 67, pp. 2223-2230; June, 1962.

8. Ellis, G. R. A., "Low Frequency Electromagnetic Radiation Associated with Magnetic Disturbances", *Planet Space Science*, vol. 1, pp. 253-258; September, 1959.

9. Gendrin, R., "Le Guidage Des Whistlers par Le Champ Magnetique", *Planet Space Science*, vol. 5, pp. 274-282; August, 1961.

10. Gintsburg, M. A., "Electromagnetic Radiation from Solar Corpuscular Streams", *Phys. Rev. Letters*, vol. 7, pp. 399-400; December, 1961.

11. McInnes, B. A., "A Study of Ionospherics at Macquaire Island", *Australian Jour. Phys.*, vol. 14, pp. 218-233; June, 1961.

12. Ondoh, T., "On the Origin of VLF Noise in the Earth's Exosphere", *Jour. Geomag. and Geoelec. Japan*, vol. 12, pp. 77-83; April, 1961.

13. Sturrock, P., "Generation of Radio Noise in the Vicinity of the Earth", *Jour. Res. NBS.*, vol. 68D, pp. 153-157; March-April, 1962.

14. Ellis, G. A. R., "Low Frequency Radio Emission from Aurorae", *Jour. Atm. and Terres. Phys.*, vol. 10, pp. 302-306; May, 1957.

15. Schwinger, J., "On the Classical Radiation of Accelerated Electrons", Phys. Rev., vol. 75, pp. 1912-1925; June, 1949.

16. Ondoh, T. "Ionospheric Absorption of Cosmic Radio Noise and Chorus at the Auroral Zone", Jour. Geomag. and Geoelec. Japan, vol. 14, pp. 133-143; April, 1963.

17. MacArthur, J. W., "Theory of the Origin of the VLF Radio Emissions from the Earth Exosphere", Phys. Rev. Letters, vol. 2, pp. 491-492; June, 1959.

18. Maeda, K and Kimura, I., "Amplification of the VLF Electromagnetic Wave by a Proton Beam Through the Exosphere", Jour. Phys. Soc. Japan, vol. 17, Suppl. A-II, pp. 92-95; January, 1962.

19. Dowden, R. L., "Doppler-Shifted Cyclotron Radiation from Electrons; A Theory of Very Low Frequency Emissions from the Exosphere", Jour. Geophys. Res., vol. 67, pp. 1745-1750; May, 1962.

20. Dowden, R. L. and Helliwell, R. A., "Very-Low-Frequency Discrete Emissions Received at Conjugate Points", Nature, vol. 195, pp. 64-65; July, 1962.

21. Dowden, R. L., "Doppler Shifted Cyclotron Generation of Exospheric Very-Low-Frequency Noise (Hiss)", Planet Space Science, vol. 11, pp. 361-369; April, 1963.

22. Lepechinsky, D. and Rolland, P., "On Plasma Instabilities and Their Probable Role in Ionospheric Phenomena", Jour. Atm. and Terres. Phys., vol. 26, pp. 31-40; January, 1964.

23. Haeff, A. V., "On the Origin of Solar Radio Noise", Phys. Rev., vol. 75, pp. 1546-1551; May, 1949.

24. Ondoh, T., "The Ionospheric Absorption of the VLF Emission at the Auroral Zone", Jour. Geomag. and Geoelec. Japan, vol. 15. pp. 90-108; November, 1963.

25. Ginzburg, V. L., "Certain Theoretical Aspects of Radiation Due to Superluminal Motion in a Medium", Soviet Phys. (USPEKHI), vol. 2, No. 6, pp. 874-893; June, 1960.

26. Ondoh, T., "A Possibility of the Generation of VLF Emissions in the Outer Earth's Exosphere", Planet Space Science Res. Note, vol. 9, pp. 69-70; January, 1962.

27. Jelly, J. V., Cerenkov Radiation and Its Application, Pergmon Press, London, p. 45; 1958.

28. Helliwell, R. A., "Whistler-Triggered Periodic Very-Low-Frequency Emission", Jour. Geophys. Res., vol. 68, pp. 5387-5396; October, 1963.

29. Brice, N., "An Explanation of Triggered Very-Low-Frequency Emissions", Jour. Geophys. Res. Letter, vol. 68, pp. 4626-4628; August, 1963.

30. Belrose, J. S. and Barrington, R. E., "VLF Noise Bands Observed by the Alouette I Satellite", Conference on Nonlinear Processes in Ionosphere NBS. Tech. Note No. 211, vol. 3, pp. 85-100; December, 1963.

31. Skinner, R. E. and Vallmer, J., "Coherent Radiation by Plasma Oscillation", Phys. Fluids Res. Note, vol. 7, pp. 148-150; January, 1964.

32. Bekefi, G., Hirshfield, J. L. and Brown, S. C., "Cyclotron Emission from Plasmas with Non-Maxwellian Distribution", Phys. Rev., vol. 122, pp. 1037-1042; May, 1961.

33. Ginzburg, V. L. and Zheleniakov, V. V., "On the Possible Mechanisms of Sporadic Solar Radio Emission (Radiation in an Isotropic Plasma). Soviet Astron., vol. 2, pp. 653-668; September-October, 1958.

34. Chow, K. K. and Pantell, R. H., "The Cyclotron Resonance Backward-Wave Oscillator", Proc. IRE, vol. 48, pp. 1865-1870; November, 1960.

35. Bell, T. F. and Buneman, O., "Plasma Instabilities in the Whistler Mode Caused by a Gyrating Electron Steam", Phys. Rev., vol. 133, pp. A1300-A1302; March, 1964.

36. Neufeld, J. and Wright, H., "Instabilities in a Plasma-Beam System Immersed in a Magnetic Field", Phys. Rev., vol. 129, pp. 1489-1507; February, 1963.

37. Helliwell, R. A., Katsufrakis, J., Trimpi, M. and Brice, N., "Artificially Stimulated Very-Low-Frequency Radiation from the Ionosphere", Jour. Geophys. Res. Letter, vol. 69, pp. 2391-2394; June, 1964.

38. Storey, L. R. O., "An Investigation of Whistling Atmospherics", Phil. Trans. Roy. Soc., vol. A246, pp. 113-141; July, 1953.

39. Allcock, G. Mck., "A Study of the Audio-Frequency Radio Phenomenon Known as 'Dawn Chorus'", Australian Jour. Phys., vol. 10, pp. 286-298; June, 1957.

40. Pope, J. H., "Diurnal Variation in the Occurrence of 'Dawn Chorus'", Nature Letter, vol. 180, p. 433; August, 1957.

41. Pope, J. H., "An Investigation of Whistlers and Chorus at High Latitudes", ASTIA No. 216,522; April, 1959.

42. Crouchley J. and Brice, N. M., "A Study of 'Chorus' Observed at Australian Stations", Planet Space Science, vol. 2, pp. 238-245; August, 1960.

43. Yoshida, S. and Hatanaka, T., "Variation in the VLF Emissions with Reference to the Exosphere", Rept. Ionos. and Space Res. Japan, vol. 16, No. 4, pp. 387-409; December, 1962.

44. Ellis, G. A. R., "Geomagnetic Disturbances and 5 Kilocycles Per Second Electromagnetic Radiation", Jour. Geophys. Res., vol. 65, pp. 1705-1710; June, 1960.

45. Tokuda, H., "VLF Emission and Geomagnetic Disturbances at the Auroral Zone--Part I: Chorus Bursts and Preceeding Geomagnetic Disturbances", Jour. Geomag. and Geoelec. Japan, vol. 14, pp. 33-40; August, 1962.

46. Ondoh, T., "Chorus Increases and Geomagnetic Pulsation at the Auroral Zone", Jour. Geomag. and Geoelec. Japan, vol. 14, pp. 86-98; October, 1962.

47. Dokuchaev, V. P, "On the Growth of Magnetohydrodynamic Waves in a Plasma Stream Moving Through an Ionized Gas", Soviet Phys. (JETP), vol. 12, pp. 292-293; February, 1961.

48. Parthasarathy, R. and Berkey, F. T., "Radio Noise from the Auroral Electrons", Jour. Atm. and Terres. Phys., vol. 26, pp. 199-204; February, 1964.

49. Gallet, R. M., "Summary of Research on VLF and ELF Emissions", Jour. Res. NBS, vol. 68D, pp. 615-618; May, 1964.

50. Tepley, L. R., "Observations of Hydromagnetic Emissions", Jour. Geophys. Res., vol. 66, pp. 1651-1658; June, 1961.

51. Watts, J. M., Koch, J. A. and Gallet, R. M., "Observations and Results from the 'Hiss Recorder' an Instrument to Continuously Observe the VLF Emissions", Jour. Res. NBS, vol. 67D, pp. 569-580; September-October, 1961.

52. Platzman, P. M. and Buchsbaum, S. J., "Effects of Collisions on the Landau Damping of Plasma Oscillations", Phys. Fluids, vol. 4, pp. 1288-1292; October, 1961.

53. Stix, T. H., "Absorption of Plasma Waves", Phys. Fluids, vol. 3, pp. 19-32; January-February, 1960.

54. Scarf, F. L., "Landau Damping and the Attenuation of Whistlers", Phys. Fluids, vol. 5, pp. 6-13; January, 1962.

55. Liemohn, H. B. and Scarf, F. L., "Exospheric Electron Temperatures from Nose Whistler Attenuation", Jour. Geophys. Res., vol. 67, pp. 1785-1790; May, 1962.

56. Pope, J. H., "A Correction to the Exospheric Electron-Density Estimate Using the Nose Whistlers of March 19, 1959", Jour. Geophys. Res. Letters, vol. 67, p. 412; January, 1962.

57. Liemohn, H. B. and Scarf, F. L., "Whistler Attenuation by Electron with $E^{-2.5}$ Distribution", Jour. Geophys. Res., vol. 67, pp. 4163-4168; October, 1962.

58. Tidman, D. A. and Jaggi, R. K., "Landau Damping of Transverse Waves in the Exosphere by Fast-Particle Fluxes", Jour. Geophys. Res., vol. 67, pp. 2215-2222; June, 1962.

59. Gordon, W. E., "Incoherent Scattering of Radio Waves by Free electrons with Application to Space Exploration by Radar", Proc. IRE, vol. 46, pp. 1824-1829; November, 1958.

60. Bowles, K. L., "Incoherent Scattering by Free Electrons as a Technique for Studying the Ionosphere and Exosphere; Some Observation and Theoretical Considerations", Jour. Res. NBS, vol. 65D, pp. 1-14; January-February, 1961.

61. Salpeter, E. E., "Electron Density Fluctuation in a Plasma", Phys. Rev., vol. 120, pp. 1528-1535; December, 1960.

62. Dougherty, J. P. and Farley, D. T., "A Theory of Incoherent Scattering of Radio Wave by a Plasma", Proc. Roy. Soc., vol. A259, pp. 79-99; November, 1960.

63. Renau, J., "Scattering of Electromagnetic Waves from a Nondegenerate Ionized Gas", Jour. Geophys. Res., vol. 65, pp. 3631-3640; November, 1960.

64. Fejer, J. A., "Scattering of Radio Waves of Ionized Gas in Thermal Equilibrium in the Presence of a Uniform Magnetic Field", Can. Jour. Phys., vol. 39, pp. 716-740; May, 1961.

65. Hagfors, T., "Density Fluctuations in a Plasma in a Magnetic Field with Applications to the Ionosphere", Jour. Geophys. Res., vol. 66, pp. 1699-1712; July, 1961.

66. Buneman, O., "Scattering of Radiation by the Fluctuation in a Non-Equilibrium Plasma", Jour. Geophys. Res., vol. 67, pp. 2050-2053; May, 1962.

67. Gardner, J. H., "Scatter from Man-Made Irregularities in Ionosphere", Jour. Geophys. Res., vol. 68, pp. 4717-4721; August, 1963.

68. Pawsey, J. L., McCready, L. L. and Gardner, F. F., "Ionospheric Thermal Radiation at Radio Frequencies", Jour. Atm. and Terres. Phys., vol. 1, pp. 261-277; May, 1951.

69. Gardner, F. F., "Ionospheric Thermal Radiation at Radio Frequencies II. Further Observation", Jour. Atm. and Terres. Phys., vol. 5, pp. 298-315; November, 1954.

70. Dowden, R. L., "Ionospheric Thermal Radiation at Radio Frequencies in the Auroral Zone", Jour. Atm. and Terres. Phys., vol. 18, pp. 8-19; April, 1960.

71. Little, C. G., Lerfald, G. M. and Parthasarathy, R., "Some Observation of 2.89 Mc/s Equivalent Antenna Temperatures at the Auroral Zone", *Jour. Atm. and Terres. Phys.*, vol. 23, pp. 275-286; December, 1961.

72. Covington, A. E., "Some Characteristics of 10.7-Centimeter Solar Noise II", *Jour. Roy. Astron. Soc. Canada*, vol. 45, pp. 49-61; April, 1951.

73. Kundu, M. R. and Haddock, F. T., "Centimeter-Wave Solar Bursts and Associated Effects", *Trans. PGAP-IRE*, vol. 9, pp. 82-88; January, 1961.

74. Hatanaka, T. "Activities of the Solar Radio Noise and the Sunspots", *Rep. Ionos. Res. Japan Short Note*, vol. 4, pp. 173-174; March, 1950.

75. Payne-Scott, R. and Little, A. G., "The Position and Movement of the Solar Disk of Sources of Radiation at a Frequency of 97 Mc/s", *Australian Jour. Sci. Res.*, vol. A5, pp. 32-46; March, 1952.

76. Roberts, J. A., "Solar Radio Bursts of Spectral Type II", *Australian Jour. Phys.*, vol. 12, pp. 327-356; December, 1959.

77. Thompson, A. R., "Spectral Observation of Solar Radio Bursts I Receiving Equipment", *Astrophys. Jour.*, vol. 133, pp. 643-648; March, 1961.

78. Wild, J. P. and McCready, L. L.,"Observation of the Spectrum of High-Intensity Solar Radiation at Meter Wavelengths", *Australian Jour. Sci. Res.*, vol. A3, pp. 387-398; September, 1950.

79. Boischot, A., "Étude du Rayonnement Radioélectrique Solaire Sur 169 Mhz. a l'Aide d'Un Grand Interféromètre a Reséau", *Ann. Astrophys.*, vol. 21, pp. 273-344; November-December, 1958.

80. McLean, D. J., "Solar Radio Emission of Spectral Type IV and Its Association with Geomagnetic Storms", *Australian Jour. Phys.*, vol. 12, pp. 404-417; December, 1959.

81. Wild, J. P., Murray, J. D. and Rowe, W. C., "Evidence of Harmonics in the Spectrum of a Solar Radio Outburst", *Nature*, vol. 172, pp. 533-534; September, 1953.

82. Wild, J. P., Murray, J. R. and Rowe, W. C., "Harmonics in the Spectra of Solar Radio Disturbances", *Australian Jour. Phys.*, vol. 7, pp. 439-459; September, 1954.

83. Wild, J. P., Sheridan, K. V. and Trent, G. H., "The Transverse Motions of the Sources of Solar Radio Bursts", *Paris Symposium on Radio Astronomy*, Stanford University Press, pp. 176-185; 1959.

84. Wild, J. P., "The Radio Emission from Solar Flares", Jour. Phys. Soc. Japan, vol. 17, Suppl. A-II, pp. 249-258; January, 1962.

85. Takanaka, T., "Acceleration of Electron in the Solar Atmosphere and Type IV Radio Outbursts", Publ. Astron. Soc. Japan, vol. 13, No. 2, pp. 166-172; February, 1961.

86. Denisse, J. F., "Les Sources d'Emissions Radioélectriques du Soleil", Paris Symposium on Radio Astronomy, Stanford University Press, pp. 86-87; 1959.

87. Wild, J. P., Roberts, J. A. and Murray, J. D., "Radio Evidence of the Ejection of Very Fast Particles from the Sun," Nature, vol. 173, pp. 532-534; March, 1954.

88. Ginzburg, V. L. and Zheleniakov, V. V., "On the Mechanisms of Sporadic Solar Radio Emission", Paris Symposium on Radio Astronomy, Stanford University Press, pp. 574-582; 1959.

89. Sen, H. K., "Space Charge Wave Amplification in Shock Front and Finite Structure of Solar Radio Noise", Australian Jour. Phys., vol. 7, pp. 30-35; March, 1954.

90. Takakura, T., "Polarized Bursts and Noise Storms of Solar Radio Emission I. Mechanism of Emission", Publ. Astron. Soc. Japan, vol. 8, pp. 182-206; March, 1956.

91. Kai, K., "Some Characteristics of Type I Burst", Publ. Astron. Soc. Japan, vol. 14, pp. 1-11; January, 1962.

92. Maxwell A. and Thompson, A. R., "Spectral Observation of Solar Radio Bursts II. Slow Draft Bursts and Coronal Streams", Astrophys. Jour., vol. 135, pp. 138-150; January, 1962.

93. Westfold, K. C., "Magnetohydrodynamics Shock Waves in the Solar Corona, with Application to Bursts of Radio-Frequency Radiation", Phil. Mag., 8th Series, vol. 2, pp. 1287-1302; November, 1957.

94. Tidman, D. A., "Radio Emission by Electrons in the Finite-Structure Electric Fields of Shock Waves", Phys. Fluids, vol. 5, pp. 1104-1112; September, 1962.

95. Wild, J. P., Sheridan, K. V. and Nyelan, A. A., "An Investigation of the Speed of the Solar Disturbances Responsible for Type III Radio Bursts", Australian Jour. Phys., vol. 12, pp. 369-398; December, 1959.

96. Ginzburg, V. L. and Zhelezniakov, V. V., "Noncoherent Mechanisms of Sporadic Solar Radio Emission in the Case of Magnetoactive Corona Plasma", Soviet Astron.--AJ., vol. 5, pp. 1-13; July-August, 1961.

97. Cohen, M. H., "Radiation in a Plasma I. Cerenkov Effect", *Phys. Rev.*, vol. 123, pp. 711-721; August, 1961.

98. Cohen. M. H., "Scattering and Conversion Cross Sections in Inhomogeneous Plasma", *Jour. Geophys. Res.*, vol. 67, pp. 2729-2740; July, 1962.

99. Malville, J. M., "Characteristics of Type III Radio Bursts", *Astrophys. Jour.*, vol. 136, pp. 266-275; July, 1962.

100. Smerd, S. F., Wild, J. P. and Sheridan, K.V., "On the Relative Position and Origin of Harmonics in the Spectra of Solar Radio Bursts of Spectral Type II and III", *Australian Jour. Phys.*, vol. 15, pp. 180-193; June, 1962.

101. Smerd, S. F.," Non-Linear Plasma Oscillations and Bursts of Solar Radio Emission", *Nature Letter*, vol. 175, p. 297; February, 1955.

102. Sturrock, P., "Non-Linear Effects in Electron Plasma", *Jour. Nucl. Energy*, *Part C* (*Plasma Physics*), vol. 2, pp. 158-163; January, 1961.

103. Cohen, M. H., "Radio Bursts from the Sun", *Symposium on Wave Interaction and Dynamic Nonlinear Phenomena in Plasma*, Penn. State University Press, pp. 118-120; 1963.

104. Sturrock, P., "Spectral Characteristics of Type II Solar Radio Bursts", *Nature Letter*, vol. 192, p. 58; October, 1961.

105. Pierce, J. R., "Possible Fluctuations in Electron Streams Due to Ions", *Jour. Appl. Phys.*, vol. 19, pp. 231-236; March, 1948.

106. Pierce, J. R., "Double-Stream Amplifiers", *Proc. IRE*, vol. 37, pp. 980-985; September, 1949.

107. Haeff, A. V., "The Electron-Wave Tube--A Novel Method of Generation and Amplification of Microwave Energy", *Proc. IRE*, vol. 37, pp. 4-10; January, 1949.

108. Feinstein, J. and Sen, H. K., "Radio Wave Generation by Multistream Charge Interaction", *Phys. Rev.*, vol. 83, pp. 405-412; July, 1951.

109. Feinstein, J., "The Conversion of Space-Charge Wave Energy into Electromagnetic Radiation", *Proc. Symposium on Electronic Waveguide*, Brooklyn Polytech. Inst. Press, pp. 345-352; 1958.

110. Sen, H. K., "Non-Linear Theory of Space-Charge Waves in Moving Interacting Electron Beam with Application to Solar Radio Noise", *Phys. Rev.*, vol. 97, pp. 849-855; February, 1955.

111. Bohm, D. and Gross, E. P., "Theory of Plasma Oscillations. A. Origin of Medium-Like Behavior", *Phys. Rev.*, vol. 75, pp. 1853-1876; June, 1949.

112. Baily, V. A., "Spontaneous Waves in Discharge Tubes and in the Solar Atmosphere", Nature, vol. 161, pp. 599-600; April, 1948.

113. Baily, V. A., "Electro-Magneto-Ionic Optics", Jour. Roy. Soc. of New South Wales, vol. L32, pp. 107-113; February, 1949.

114. Baily, V. A., "Plane Waves in an Ionized Gas with Static Electric and Magnetic Field Present", Australian Jour. Sci. Res., vol. 1, pp. 351-359; December, 1948.

115. Baily, V. A., "On the Relativistic Electromagnetic-Ionic Theory of Wave Propagation", Phys. Rev. Letters, vol. 77, pp. 418-419; February, 1950.

116. Walker, L. R., "Note on Wave Amplification by Interaction with a Stream of Electrons", Phys. Rev. Letters, vol. 76, pp. 1721-1722; December, 1949.

117. Baily, V. A., "The Relativistic Theory of Electro-Magneto-Ionic Waves", Phys. Rev. vol. 83, pp. 439-454; July, 1951.