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MICROWAVE EMISSION AND SCATTERING FROM EARTH SURFACE AND ATMOSPHERE

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Microwave Emission and Scattering from Earth Surface and Atmosphere

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SEMI-ANNUAL PROGRESS REPORT

1. INTRODUCTION

Nonlinear EM wave interactions with the upper atmosphere have been investigated during the period 15 December 1985–16 June 1986 on the following subjects: (1) the simultaneous excitation of ionospheric density irregularities and earth's magnetic field fluctuations [1,2], (2) the electron acceleration by Langmuir wave turbulence [1], and (3) the occurrence of artificial spread F [1,3]. While processes (2) and (3) can be caused only by HF waves, process (1) occurs with EM frequencies as low as in the VLF band and as high as in the SHF band.

Radio measurements of Total Electron Content (TEC) and optical detection of airglow variations show that large scale plasma patches appearing in the high latitude ionosphere have irregular structures, evidenced by the satellite phase and amplitude scintillations. Whistler waves, intense quasi-DC electric fields, atmospheric gravity waves, and electrojets are potential sources of various plasma instabilities. The role of thermal effects in generating ionospheric irregularities by these sources have been investigated [4–6]. A model has been developed to explain the discrete spectrum of the resonant ULF waves that have been commonly observed in the magnetosphere [7]. The resonant electron diffusion is suggested to be an effective saturation process of the auroral kilometric radiation [8]. The calculated intensity of the saturated radiation has a significantly lower value in comparison with that caused by the quasi-linear diffusion process as an alternative saturation process.

2. RESEARCH PROGRESS

(a) Simultaneous excitation of ionospheric density irregularities and earth's magnetic field fluctuations

Radio waves, if intense enough, are able to excite thermal filamentation instability in the ionosphere and magnetosphere, that produces sideband and purely growing modes with wave vectors perpendicular to the propagation direction of radio waves. Magnetic field-aligned nonoscillatory modes (i.e., filaments of magnetostatic and ionospheric density fluctuations) are formed along the radio wave paths. They are caused by a nonlinear thermal effect due to radio wave-plasma interactions. We elucidate its physical mechanism as follows.

The wave fields, that include the incident and sideband fields, interact with plasmas and consequently yields two types of nonlinear force. In generating field-aligned nonoscillatory modes, the thermal pressure force turns out to be larger than the ponderomotive force by a factor of $(\lambda/2\pi r_e)^2$ for modes with scale lengths λ less than $\pi r_e(2M/m)^{1/2}$ (~ 15 m in the ionosphere) and by a factor of (M/m) otherwise, where r_e and (M/m) are the electron gyroradius and the ratio of ion to electron masses, respectively. Ions cannot be effectively heated because of large cross-field heat diffusion loss. Thermal pressure force can be built up only in the electron gas across the earth's magnetic field, B_0.

Electron density fluctuations (δN) that are induced consequently by the thermal pressure force give rise to a self-consistent field ($\delta \mathbf{E} = \hat{x}\delta E$) associated with the excitation of the purely growing mode. While the net force acting on electrons is $(\mathbf{f}_T - eN_0\delta\mathbf{E})$, that on singly charged ions is $eN_0\delta\mathbf{E}$. These wave-induced forces combined with the orthogonal earth's magnetic field result in cross-field drift motions of electrons and ions at the velocities of $(\delta\mathbf{E} - \mathbf{f}_T/eN_0) \times \mathbf{B}_0/B_0^2$ and $(\delta\mathbf{E} \times \mathbf{B}_0/B_0^2)$, respectively. Therefore a relative motion between electrons and ions at the velocity of $(\mathbf{f}_T/eN_0) \times \mathbf{B}_0/B_0^2$ results and produces a net current flowing along the direction of the y axis. This wave-induced current (and vector potential, $\delta\mathbf{A}$) varies sinusoidally along the x axis. It can be visualized as a combination of many sheetlike currents on the y-z plane with a thickness of half the scale length λ, flowing in the opposite directions alternately. Or, equivalently, pairs of dipole current form within the radio wave-heated ionospheric region. Earth's magnetic field fluctuations $\delta\mathbf{B}$ that result from the radio wave-induced current are field aligned. They point in the same direction as the geomagnetic field's, $\mathbf{B}_0$, because $\nabla \times \delta\mathbf{A} = \delta\mathbf{B} = \hat{z}\delta B$.

In summary, electron temperature perturbation δT_e caused by radio wave heating prduces a cross-field thermal pressure force $\mathbf{f}_T$ as the key nonlinearity of the thermal filamentation instability. This nonlinear force induces earth's magnetic field perturbation $\delta\mathbf{B}$ and ionospheric density irregularities δN that, subsequently, cause nonuniform electron heating and , then, perturbs the electron temperature in turn. It can be expected from the above delineated physical picture that $\delta N \propto \delta B$ because both of them are induced in proportion by $\mathbf{f}_T$. Such a relation has been, indeed, found in our detailed formulation of the theory.

The thermal filamentation instability of VLF waves (whistlers) can be excited in the magnetosphere rather than the ionosphere. This is because the instability can only be excited in the frequency range $\Omega_e/2 < \omega_0 < \Omega_e$ by whistlers and $\Omega_e/2\pi$ is about 1.4 MHz in the ionosphere and 13.65 KHz in the magnetosphere at $L = 4$. Although VLF wave injection experiments have been performed actively, for example, at Siple, Antarctica, the ground-based transmitters are usually operated in a pulsed-wave mode with duration of a few seconds. These VLF wave pulses have been used to study, primarily, coherent wave-particle interactions in the magnetosphere such as the wave amplification, the triggering of wave emissions, the induced particle precipitation, etc. However, the excitation of thermal filamentation instability in the magnetosphere requires the continuous operation of VLF transmitters for a few minutes because of the small electron collision frequency (~ 0.1 Hz) and then the small growth rates (10^{-3} to 10^{-2} Hz). Experiments can be planned with the Siple transmitter of more powerful U.S. Navy communication transmitters operated in CW modes and also with spacecrafts, for instance, the ISEE 1 to monitor the VLF wave-induced magnetospheric disturbances.

The thermal filamentation instability can be excited in the ionosphere by radio waves whose frequencies exceed half the electron gyrofrequency (~ 0.7 MHz). The ionospheric heating facilities located at Arecibo and Tromsø currently operate in the HF band at lowest frequencies of the order of 3 MHz. Those in U.S.S.R. are also primarily HF transmitters except the one near Moscow that operates at a frequency (~ 1.35 MHz) near the electron gyrofrequency. Unexpectedly large geomagnetic field perturbation of the order of 10 nT had been caused by the Tromsø transmitter and we explain it in terms of the thermal filamentation instability. this instability needs several minutes to be developed under the experimental conditions at Tromsø. This characteristic growth time is consistent with the observations that geomagnetic perturbation increased regularly with the operation time of radio waves in the range from 10 to 360 s.

It has been predicted that the conceptualized Solar Power Satellite (SPS) will produce large-scale ionospheric irregularities and also possibly together with the simultaneous excitation of earth's magnetic field fluctuations [9]. A rocket experiment named Microwave Ionosphere Nonlinear Interaction Experiment (MINIX) was carried out recently by the Kyoto University group in Japan to simulate the SPS [10]. The microwaves were transmitted at a frequency of 2.45 GHz with incident power densities comparable to the envisioned intensity of 230 W/m^2 in SPS. The beam width of order of a few meters is, however, less than that (~ 10 km) proposed for SPS by, at least, 3 orders of magnitude. The excitation of electorn cyclotron waves and electron plasma waves were observed, but it is not surprising that ionospheric irregularities and other predicted phenomena could not be produced in

MINIX because of the rather narrow microwave beam. The beam size is probably a very crucial parameter in the simulation experiments of SPS.

(b) Electron acceleration by Langmuir wave turbulence

The process of electron accerlation by plasma turbulence in the HF-modified ionosphere was investigated. Langmuir waves excited parametrically during HF radio wave heating of the ionosphere are considered to be the source of generating energetic electrons (> 10 eV), whose existence was first deduced from the measurements of enhanced plasma lines [11a,11b] and confirmed later in *in situ* particle measurements [12]. The electron diffusion effect of the Langmuir wave field on electron distribution was analyzed by deriving a velocity distribution equation for electron plasmas embedded in a uniform magnetic field in the presence of a broad spectrum of Langmuir waves. Both the quasi-linear and the non-linear processes of wave-particle interactions were included in the formulation. The analysis begins with the collisionless Vlasov equation, which is analyzed as follows.

The distribution function, f, is separated into the averaged background part, $\langle f \rangle$, and the fluctuation part, $\tilde{f}$. Integrating the resulting equation for the fluctuating part along the quasi-linear and the non-linear wave-particle interactions. Then, substituting this result of density perturbation into the equation for the background distribution leads to a diffusion equaiton for $\langle f \rangle$. Since we are only interested in the diffusion process along the magnetic field, and assume that the transverse component of the distribution function remains Maxwellian, i.e. let $\langle f \rangle = h(v_\perp)g(v_z,t)$, where $h(v_\perp) = (m/2\pi T_e)\exp[-mv_\perp^2/2T_e]$, the diffusion equation is integrated over $v_\perp$ to yield a modified Fokker-Plank equation for $g(v_z,t)$, viz.

$$\frac{\partial}{\partial t}g = \frac{\partial}{\partial v_z}\left(D\frac{\partial}{\partial v_z} - A\right)g - \frac{\partial^2}{\partial v_z^2}\left(D_1\frac{\partial}{\partial v_z} - A_1\right)g$$

where $D = D^L + D_-^{NL} + D_+^{NL}$, $A = A^L + A_-^{NL} + A_+^{NL}$, $D_1 = D_{1-} + D_{1+}$ and $A_1 = A_{1-} + A_{1+}$;

D^L and A^L are the quasi-linear diffusion and friction coefficients; D_-^{NL}, A_-^{NL}, D_{1-} and A_{1-} represent the non-linear wave-particle interactions with the Langmuir waves propagating the same direction and D_+^{NL}, A_+^{NL}, D_{1+} and A_{1+} with the two waves propagating opposite to each other.

For evaluation of the coefficients, an idealized model for the Langmuir wave spectrum is used

$$|\phi|^2 = \begin{cases} \frac{3.4(v_e/\omega_0)p^2 n_0 T_e}{(1-p^{-1/2})k_m^4}\delta(k-k_m) & \text{for } 0 \le \theta \le \theta_0 \text{ and } \pi-\theta_0 \le \theta \le \pi \\ 0 & \text{for } \theta_0 < \theta < \pi - \theta_0 \end{cases}$$

where θ is the angle between the Langmuir wave vector k and the magnetic field $\mathbf{B}_0$; k_m corresponds to the Langmuir waves having peak intensities; θ_0 defined by $\cos^{-1}(p^{-1/2})$ is the maximum θ of the Langmuir waves, where p is the squared ratio of the local electromagnetic pump field to the threshold field of the parametric decay instability. The other parameters n_0, T_e, v_e and ω_0 have their conventional meanings of plasma density, electron temperature, effective electron collision frequency and angular pump wave frequency, respectively.

To achieve the electron acceleration from the bulk region to the tail, the diffusion coefficients must remain non-vanishing throughout a wide range of the velocity space. The conditions for electron acceleration were determined. It was found that a wide range of v_z is covered by quasi-linear diffusion alone with the aid of cyclotron harmonic shift. In each cyclotron shifted region, the quasi-linear steady-state solution has the Maxwellian form

$$g(v_z, t \to \infty) \propto \exp\{(m/2T_e)[l\Omega/(\omega_m - l\Omega)v_z^2]\}$$

with an effective temperature defined by $T_{eff} = (l\Omega - \omega_m)T_e/l\Omega$, where l is the cyclotron harmonic number and it satisfies $l < (\omega_m/\Omega) - (1-\cos\theta_0)^{-1}$ or $l > (\omega_m/\Omega) + (1-\cos\theta_0)^{-1}$. In the region of very large $|v_z|$, i.e. the very large $|l|$ case, the effective temperature (T_{eff})

approaches the unperturbed electron temperature (T_e). Hence, very energetic electrons (say, > 20 eV) are not expected to be produced by the quasi-linear diffusion process. This is because quasi-linear diffusion is impeded by the associated friction force A^L which arises from a finite Larmour radius effect. Therefore, we examine the non-linear wave-particle interaction. We first realize that $A_-^{NL}/D_-^{NL} \sim -(m/T_e)v_z \sim A_{1-}/D_{1-}$, indicating that the diffusion of electrons is also impeded by friction and no energetic electron flux can be produced in the case of the non-linear wave-particle interaction with Langmuir wave pairs propagating in the same direction. In the other case D_+^{NL}, A_+^{NL}, A_{1+} and D_{1+} are found to exist in two velocity regions: one region overlaps with the quasi-linear diffusion region and the other one covers all the energetic electron velocity region. These two velocity regions overlap where the pump level is strong, i.e. $p \geq 9$, and hence continuous acceleration of electrons from the bulk region to the very energetic tail region can, in principle, be achieved. In this very energetic region, $D_{1+} \sim v_z D_+^{NL}$ and $A_+^{NL} \sim 0 \sim A_{1+}$, and a plateau for the steady-state distribution function results.

In summary, our analyses show that quasi-linear diffusion may be effective enough to produce the energetic electron flux (> 10 eV) reported in [11b]. However, the very energetic electrons (> 25 eV) [12] can only be generated by the diffusion process through non-linear wave-particle interaction with the Langmuir wave pairs propagating opposite to each other.

(c) Occurrence of artificial spread F echoes

Artificial spread F that refers to diffuse echoes on an ionogram from the ionospheric F region was observed in the ionospheric heating experiments conducted at Boulder, Colorado [13]. This ionospheric phenomenon is generally believed to be caused by the excitation of large-scale (a few hundreds of meters to kilometers) field-aligned ionospheric irregularities. However, spread F is a rare phenomenon in the experiments at Arecibo, Puerto Rico [14] and it has not been observed at Tromsø, Norway since the new European heating facility has been in operation [15]. Evidences, such as the radio star scintillations [15] and the sanning radar incoherent backscatter process [17] indicate that large-scale ionospheric irregularities hve been excited by HF heater waves at Tromsø and Arecibo. Hence a lack of spread F echoes does not imply the absence of heater wave-induced ionospheric irregularities. It may be due to the difference in the polarization directions of the HF wave-induced irregularities where the polarization direction of the irregularities where the polarization direction of the irregularity is defined to be the direction of its wave vector. In general, field-aligned irregularities can have two independent polarization directions. One lies in the meridian plane and the other one is in the direction perpendicular to the meridian plane. The theoretical results of filamentation instability in magnetoplasmas [18] also show that the irregularities excited by the o mode pump and by the x mode pump have different polarization directions. The irregularities excited by the o mode pump are field-aligned and are polarized in the direction perpendicular to the meridian plane. By contrast, the irregularities excited by the x mode pump are polarized in the meridian plane and are, in general, not field-aligned. However, the field-aligned nature of the irregularities may be established to reduce the diffusion damping along the magnetic field.

Since spread F is generally used as an indicator of large-scale irregularities, and yet it is known that sometimes such irregularities do not produce spread F. Hence a study leading to better understanding of the spread F phenomenon and its relationship with density irregularities is thought to be important in this aspect. In the present work a theoretical model for artificial spread F echoes is developed, from which the relationship between the spread F echoes and the HF wave-induced irregularities is studied. The primary purpose of this study is to determine the effects of the irregularity polarizations, scale length, and the magnetic dipangle on the spread F echo.

We interpret that spread F echoes result from the drastic variation of reflection heights of vertically transmitted radio waves in the presence of ionospheric irregularities.

This problem can be understood from analyzing the trajectory of rays described by the following Hamiltonian equations of motion

$$d\vec{r}/dt = \partial\omega/d\vec{k} \tag{1a}$$

$$d\vec{k}/dt = -\nabla\omega \tag{1b}$$

where ω and $\vec{k}$ are the wave frequency and wave vector of transmitted radio waves from the ionosonde; $\vec{r}$ and t have their conventional meanings of displacement and time, respectively. If $\omega^2 \gg \Omega^2$, is assumed, the dispersion relation of radio waves in the ionosphere is simply represented by

$$\omega^2 = \omega_{pe}^2 + k^2c^2 \tag{2}$$

where ω_{pe} and c are electron plasma frequency and the speed of light in vacuum.

The unperturbed ionospheric density is modelled by $N_0(x) = N_0(1 + x/L)$ for a horizontally stratified ionosphere having a scale length L, where x is the vertical coordinate and N_0 is the electron density at the reference plane $x = 0$ located at an altitude of H above the earth crest. Field-aligned ionospheric irregularities can, in general, have two independent polarization directions. One lies in the meridian plane, the electron density fluctuations then have the form of $\delta N_1 \sin k_1(x\cos\theta_0 + z\sin\theta_0)$, where k_1 is the average wave number of the irregularities, θ_0 is the local magnetic dip angle, and z is the horizontal coordinate. The other one is oriented perpendicularly to the meridian plane, the electron density fluctuations can be modelled as $\delta N_2 \sin(k_2 y + \phi)$, where k_2 is the average wave number of this type of irregularities, y is the coordinate perpendicular to the meridian plane, and ϕ is an arbitrary phase angle.

In the presence of ionospheric irregularities the electron density distribution,

$n(x, y, z)$, includes the unperturbed and the fluctuating components. the electron plasma frequency, ω_{pe}, then has the following expression

$$\omega_{pe}/\omega_{peo} = [1 + x/L + (\delta N_1/N_0)\sin k_1(x\cos\theta_0 + z\sin\theta_0) + (\delta N_2/N_0)\sin(k_2 y + \phi)]^{1/2} \tag{3}$$

where ω_{peo} is the electron plasma frequency at the refernece plane, $x = 0$. Consequently, the trajectory of rays in the Cartesian system of coordinate is governed by the following six scalar equations

$$\frac{d}{dt}x = \frac{k_x c^2}{\omega} \tag{4a}$$
$$\frac{d}{dt}y = \frac{k_y c^2}{\omega} \tag{4b}$$
$$\frac{d}{dt}z = \frac{k_z c^2}{\omega} \tag{4c}$$
$$\frac{d}{dt}k_x = -\frac{\omega_{peo}^2}{2\omega L}\left[1 + \left(\frac{\delta N_1}{N_0}\right)(k_1 L\cos\theta_0)\cos k_1(x\cos\theta_0 + z\sin\theta_0)\right] \tag{5a}$$
$$\frac{d}{dt}k_y = -\frac{\omega_{peo}^2}{2\omega}\left(\frac{\delta N_2}{N_0}\right)k_2\cos(k_2 y - \phi) \tag{5b}$$
$$\frac{d}{dt}k_z = -\tan\theta_0\left(\frac{\omega_{peo}^2}{2\omega L}\right)\left(\frac{\delta N_1}{N_0}\right)(k_1 L\cos\theta_0)\cos k_1(x\cos\theta_0 + z\sin\theta_0) \tag{5c}$$

Equations (4b) and (5b) form one set of coupled equations and equations (4a), (4c), (5a), and (5c) form the other one.

Four invariants of ray trajectory have been found, they are

$$\left(\frac{\delta N_2}{N_0}\right)\sin(k_2 y + \phi) + \left(\frac{k_y^2 c^2}{\omega_{peo}^2}\right) = \tau_1 \tag{6}$$

$$k_x - k_z\cot\theta_0 + \left(\frac{\omega_{peo}^2}{2\omega L}\right)t = \tau_2 \tag{7}$$

$$x + \left(\frac{\tan 2\theta_0}{2}\right) z + \left(\frac{\delta N_1}{N_0}\right) L \left(\frac{\cos^2\theta_0}{\cos 2\theta_0}\right) \sin k_1(x\cos\theta_0 + z\sin\theta_0)$$
$$+ \left(\frac{c^2 L}{\omega_{peo}^2}\right) k_x(k_x + k_z \tan 2\theta_0) = \tau_3 \tag{8}$$

$$\left(\frac{\tan 2\theta_0}{2}\right) z + \left(\frac{\delta N_1}{N_0}\right) L \left(\frac{\sin^2\theta_0}{\cos 2\theta}\right) \sin k_1(x\cos\theta_0 + z\sin\theta_0)$$
$$- \left(\frac{c^2 L}{\omega_{peo}^2}\right) k_z(k_z - k_x \tan 2\theta_0) = \tau_4 \tag{9}$$

where τ_1, τ_2, τ_3, and τ_4 are four constants in time. With the aid of these four invariant relations, the temporal evolution of any one of x, z, k_x, and k_z, and either one of y and k_y can be determined by the corresponding equations of ray trajectory, namely, (4) and (5).

The elapsed time for each ray travelling from the reference height to the reflection height can, in principle, be calculated by integrating (5a) from $k_x = k_{x0}$ to $k_x = 0$ with the prescribed initial conditions: $x(t=0) = 0$, $z(t=0) = z_0$, and $k_z(t=0) = k_{z0}$ and with the aid of the invariant relations (7), (8), and (9). It is clear from (5a) that k_x is only affected by ionospheric irregularites (referred to as type A irregularities) whose polarization lies within the meridian plane. Those (referred to as type B irregularities) whose polarization is oriented perpendicularly to the meridian plane do not cause the variation of reflection heights of radio waves. Types A and B irregularities can be excited by the filamentation instability of X-mode and O-modes HF heater waves, respectively [18].

If the ionosonde-transmitted beam is modelled by many rays having different inital locations on the reference plane, the spread F echoes can be interpreted to be caused by the difference in the reflection heights of the returned signals. The virtual height spread in the ionogram is thus proportional to the maximum difference Δx_{max}, of these reflection heights. The quantitative analysis of our spread F echo model show that (1)

Δx_{max} increases monotonically with the irregularity intensity, (2) with a fixed irregularity intensity, Δx_{max} increases with latitudes and then decreases monotonically to zero at $\theta_0 = 90°$, (3) significant spread F (i.e., large Δx_{max}) can be observed over a wide range of latitude including Arecibo ($\theta_0 = 50°$), Boulder ($\theta_0 = 68°$), and even Tromsø ($\theta_0 = 78°$) as long as type A irregularities exist, and (4) spread F occurs with $\lambda_\perp > 100$ meters, where $\lambda_\perp$ is the scale length of type A ionospheric irreuglarities. These results indicate that the appearance of the spread F should not depend upon the locations of ionosondes. We conclude that HF heater wave-induced spread F's are caused by type A irregularities with scale lengths greater than 100 meters.

Based upon our model of spread F echoes, we can explain the different occurrence frequency of artificial spread F's noticed at Arecibo, Boulder, and Tromsø as follows. The HF heater wave transmitted from Tromsø, Norway is either a left (X-mode) or right (O-mode) hand circularly polarized wave propagating along the geomagnetic field. Large-scale irregularities would be excited by the filamentation instability preferentially in the direction perpendicular to the meridian plane for symmetric high frequency sidebands [18]. This together with the effect of large geomagnetic dip angle ($\theta = 78°$), may explain why artificial spread F's have never been observed at Tromsø since the EISCAT heating facilities were operated a few years ago. The HF heater at Arecibo is often operated in O-mode. During the O-mode ionospheric heating, no spread F or change of reflection heights can be seen. This can be understood now with the proposed model of spread F echoes, namely, spread F cannot be induced by type B irregularities produced by O-mode heater waves. Finallly, we discuss the reason why artificial spread F had been constantly observed at Boulder, Colorado. It is most possibly because the O-mode and X-mode heater waves transmitted from the Boulder facilities cannot be separated as easily as those from the Arecibo or the Tromsø facilities. This speculation is based upon the fact that short-scaled (meter-scaled and less) irregularities can still be excited by X-mode heater waves at Boulder though not expected [19]. According to existing theories only O-mode waves are able to generate short scale ionospheric irregularities.

(d) High-latitude ionospheric density irregularities

Some sources and causes of high latitude ionospheric irregularities have been preliminarily examined with emphasis on the resultant thermal effects that excite "thermal plasma instabilities". The basic processes are the generation of plasma temperature perturbations (δT) and the subsequent coupling with plasma density fluctuations (δn). More specifically significant temperature perturbations in the electron (or ion) gas give rise to a thermal pressure force, $-\nabla(n_0 \delta T)$, acting on electrons (or ions) only. The charge separation (δn) consequently formed establishes a self-consistent field, $\vec{E}_s$, that is associated with the excitation of ionospheric density irregularities (δn). A threshold condition is required for these thermal instabilities because the excited ionospheric irregularities are not normal modes of the ionosphere but nonlinearly driven modes by a thermal pressure force. These ionospheric irregularities are electrostatic disturbances in nature connected with exactly or nearly zero frequency (i.e., purely growing) modes. Because of their standing wave pattern, these ionospheric irregularities do not propagate. Hence, the radar echoes from these irregularities do not have Doppler shifts.

Whistler waves can produce ionospheric irregularities in both the E and F regions with scale lengths ranging from a few meters to a few tens of meters. Plasma blobs (or patches) appearing in the high latitude ionospheric F region provide a favorable environment for the instability related to the thermal effect caused by the quasi-DC electric field. This thermal instability is effective in structuring plasma blobs (or patches) with medium-scale density irregularities ranging from tens of meters to a few kilometers. Large-scale irregularities can be excited by gravity waves with short periods $<$ 1 hour) and short scale lengths ($\sim$ tens of kilometers to a few hundreds of kilometers) directly in the E rather than the F rgion. However, the gravity wave-induced electric field (associated with ionospheric irregularities) in the E region is able to map up to the F region along the geomagnetic field and then structure the F region. Short-scale irregularities generally have larger growth rates, for instance, meter-scale irregularities can be excited within fractions of a second or at most several seconds, but the hundreds - and larger scale irregularities need a few minutes to be developed. After the sources of thermal instabilities disappear, irregularities are weakened by the cross-field diffusion damping that depends upon the irregularity scale lengths. While kilometer- and larger-scale irregularitites can survive for hours, the meter-scale irregularities decay within seconds.

In summary, whistler waves create short-lived, short-scale ionospheric irregularities in the E and F regions. Medium-scale irregularities are generated throughout the plasma blobs (or patches) by the thermal instability connected with intense quasi-DC electric field. Gravity wave-induced large-scale irregularities extend from the lower to the upper ionospheres. These three mechanisms, characterized by various thermal effects, can contribute additively with other processes to the occurrence of irregularities in the high latitude ionosphere.

(e) Saturation of auroral kilometric radiation

Coherent electromagnetic radiation can be generated in a magnetized non-Maxwellian plasma by the synchrotron maser instability. This instability occurs under the conditions of inverted population, and stems from the relativistic mass dependence of the electron gyrofrequency that gives rise to phase bunching in the electron gyration orbits. The operation of this instability has been suggested [20, 21] to be responsible for auroral kilometric radiation.

The optimum environment for the excitation of this instability in space plasmas is provided by the following processes that invert the population and form the non-Maxwellian electron distribution for lasing. Kilovolt electric potential drops are believed to exist along the auroral field lines during the inverted-V events [22, 23]. Although the depletion of the background electrons to a very low level is expected because of the parallel electric field, the upgoing electrons that originate in the reflected plasma-sheet electrons introduce a loss-cone distribution. The non-Maxwellian electron distribution thus created is capable of producing intense coherent electromagnetic radiation in the upper atmosphere.

The synchrotron maser instability converts the electron energy into coherent radiation. More specifically, the amplification of electromagnetic radiation occurs at the expense of the kinetic energy of electrons whose perpendicular momentum falls in the range where the electron distribution function has a positive slope. The saturation of this instability is, therefore, carried out by processes that can decrease the positive slope of the momentum distribution. A quasi-linear level of the auroral kilometric radiaiton. This diffusion process suppresses the instability by driving electrons into the lower velocity region, i.e. by reducing the positive gradient of the electron distribution function. Since the radiation frequency is less than, but very close to, the electron gyrofrequency, resonance broadening was also examined [24] as another potential saturation process. They found that the saturation wave energy would be one order of magnitude higher if resonance broadening, rather than quasi-linear diffusion, were considered to be the primary saturation process. In other words, quasi-linear diffusion dominates over resonance broadening as a saturation process of the synchrotron maser instability in generating auroral kilometric radiation.

We have formulated the theory of resonant electron diffusion as an alternative saturation process of the synchrotron maser instability driven by a loss-cone electron distribution. We were motivated by the computer simulation work of Wagner et al. (1983) [25]. They showed that auroral kilometric radiation amplified by the synchrotron maser instability saturates when the resonant electrons diffuse into the loss cone via turbulent scattering of electrons by the excited radiation. We are able to evaluate analytically the intensity of the saturated auroral kilometric radiation. The ratio ($\simeq 8.7 \times 10^{-5}$) of the saturated wave energy to the kinetic energy, is less than that ($\simeq 2.0 \times 10^{-3}$) obtained in computer simulation by a factor of about 20 because different distribution functions and parameters are used.

The main purpose of this work is to find out whether resonant diffusion indeed dominates over quasi-linear diffusion in causing the saturation of auroral kilometric radiation. The saturated radiation intensity has been calculated with the same distribution function and plamas parameters that were employed in [26] for the analysis of the quasi-linear diffusion process. We conclude, therefore, that resonant electron diffusion provides the dominant process for saturating the synchrotron maser instability in the generation of auroral kilometric radiation as demonstrated in the computer simulation [25].

3. PROBLEMS UNDER INVESTIGATION

While continued effort will be placed on the aforesaid research in occurrence of artificial spread F echoes, high-latitude ionospheric density irregularities, and auroral kilometric radiation, we plan to study the following new subjects: (1) the nonlinear interactions of electromagnetic waves with the ionosphere that can alter the characterics of the waves, (2) ionospheric effects on satellite communications such as the Faraday polarization fluctuations caused by ionospheric density fluctuations, and (3) mechanisms leading to spectral broadening of transmitted VLF waves.

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