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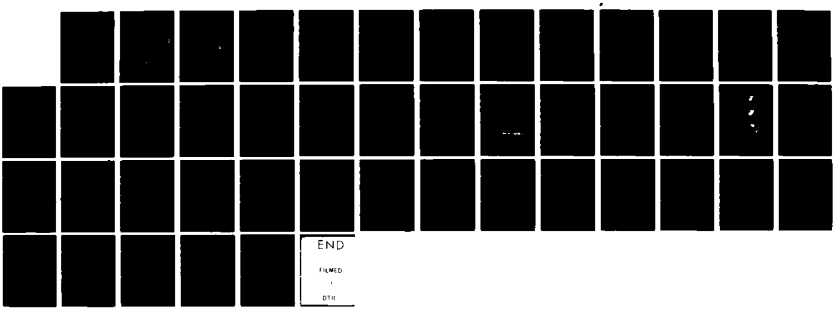

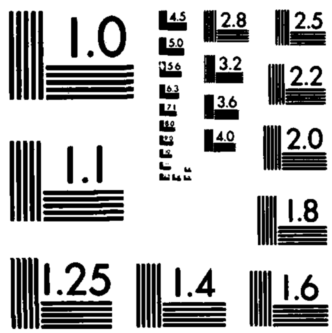

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Theories of High Latitude Ionospheric Irregularities: A Review*

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November 17, 1982

*Text of invited talk presented at URSI Symposium on "Radio Probing of the High-Latitude Ionosphere and Atmosphere," Fairbanks, Alaska, August 1982.

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A review of theories of naturally occurring high latitude E and F region ionospheric irregularities and structure is presented. Emphasis is placed on irregularity source mechanisms. Recent theoretical results are stressed.

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CONTENTS

THEORIES OF HIGH LATITUDE IONOSPHERE IRREGULARITIES: A REVIEW*

1. INTRODUCTION

Using a variety of experimental techniques, e.g., satellites [Dyson, 1969; Dyson et al., 1974; Sagalyn et al., 1974; Clark and Raitt, 1976; Phelps and Sagalyn, 1976; Rodriguez et al., 1981], rockets [Olesen et al., 1976; Ogawa et al., 1976; Kelley et al., 1980], scintillations [Aarons et al., 1969; Fremouw et al., 1977; Erukhimov et al., 1981], and radar backscatter [Weaver, 1965; Greenwald,, 1974; Hower et al., 1966; Vickrey et al., 1980; Hanuise et al., 1981], it is now known that the high latitude ionosphere, from the auroral zone into the polar cap, is a highly structured and nonequilibrium medium containing irregularities (plasma density fluctuations and structures) with scale sizes ranging from hundreds of kilometers to meters. Aside from being an interesting scientific phenomenon, ionospheric irregularities are of practical interest to the radio-physics community since they can disrupt transionospheric radio wave communications channels (see recent review by Davies [1981] and references therein).

Several theories, e.g., particle precipitation, plasma instabilities and processes, and neutral fluid dynamics have been proposed to account for high latitude ionospheric irregularities. Recently, considerable quantitative progress has been made, especially in the area of ionospheric plasma instabilities, in identifying the physical processes that can lead to high latitude irregularities. With the advent of the EISCAT incoherent scatter radar and new radar facilities to be constructed in Greenland, it seems timely to review the current state of theoretical research dealing with high latitude ionospheric irregularities. As a result, we present, in this paper, an overview of theories of naturally occurring high latitude E and F region ionospheric irregularities. (For a review of artificially induced irregularities, e.g., from ionospheric 'heating' experiments, see Fejer [1979].) Emphasis will be placed on recent results, particularly with regard to sources of high latitude irregularities. Physical mechanisms will be stressed with extensive mathematical analysis avoided. Expertise in plasma physics has not been assumed. ~~In Section 2~~ we summarize the recent and previous theoretical literature dealing with F region irregularities, and ~~while in Section~~ we concentrate on E region irregularity phenomena.

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2. HIGH LATITUDE F REGION IRREGULARITIES

The high latitude latitude ionosphere is profoundly affected by particle precipitation, currents both parallel and perpendicular to the geomagnetic field, plasma transport, and thermospheric heating. In the high latitude F region ionosphere, several irregularity source mechanisms have been proposed: particle precipitation, plasma processes and instabilities, and neutral fluid dynamics. We now discuss each of these sources separately and point out the irregularity spatial scale size regimes in which they are believed to operate.

2.1 Structure from particle precipitation

Particle precipitation is expected to play an important role in structuring the high latitude F region ionosphere. Rees [1963] has shown that low energy 10^2-10^3 eV electrons deposit most of their energy at auroral F layer altitudes. As a result, spatial and temporal structure in the electron fluxes might be mirrored in the ambient ionospheric plasma. Evidence for this hypothesis was presented by Dyson and Winningham [1974] who showed good correlation between structure in low energy electron fluxes and electron density in the polar cusp. In addition they indicated that the equatorward boundary of irregularities in the pre-noon cusp is nearly collocated with the boundary for soft (~ 300 ev) auroral electron fluxes. The structure inherent in the electron fluxes presumably derives from processes occurring in the plasma sheet but no quantitative studies of this structure have been performed to date. Recently, Kelley et al. [1982] gave further evidence that structured low energy electron precipitation is a source of large scale ($\lambda > 10$ km) high latitude F region ionization irregularities. They performed a spatial Fourier analysis of the electron density irregularities found by Dyson and Winningham [1974] and found irregularity scale sizes distributed from approximately 75 km to 0.75 km. The power spectra of these irregularities could be described by a power law proportional to $k^{-1.89}$.

Recently, Vickrey et al. [1980], using the Chatanika incoherent scatter radar, have studied large scale aproximately magnetic field aligned convecting plasma enhancements in the midnight sector auroral F region (see Fig. 1).

These ionization enhancements, which can have their plasma density enhanced by factors of two to ten over background ambient values, have been observed in regions of diffuse auroral particle precipitation and associated field aligned currents. The occurrence of the plasma enhancements is apparently not strongly related to magnetic activity or to E region processes. The overall north-south dimensions of some of the observed plasma enhancements is comparable to the outer scale sizes of the electron density structures associated with auroral F region particle precipitation events [Kelley et al., 1982]. As a result, the structured low energy particle precipitation may be an important source of the large scale F region structure associated with these plasma enhancements. Large scale east-west structure associated with the plasma enhancements has also been demonstrated [Tsunoda and Vickrey, 1982]. In addition, spatial spectral analysis of these enhancements [Kelley et al., 1982] have indicated structure from approximately 50 km down to several kilometers. The presence of smaller kilometer and hundreds of meter sized plasma density irregularities collocated with these enhancements has been verified using satellite scintillation studies [Fremouw et al., 1977; Rino et al., 1978; Vickrey et al., 1980]. The scintillation measurements have indicated that the electron density irregularities are structured like L shell aligned sheets for equatorward convection of the plasma enhancements.

Similar observations [Weber and Buchau, 1981] of correlations between structured strongly enhanced F region plasma and low energy electron precipitation have also been reported for the polar cap ionosphere.

2.2 Structure from plasma processes and instabilities

It is logical to consider plasma processes in discussing high latitude ionospheric irregularities since several sources of free energy are available to drive various plasma instabilities. Examples of these sources include density gradients, velocity shears, and currents both parallel and perpendicular to the geomagnetic field. Both plasma macroinstabilities, which are fluidlike and operate on scale sizes $\lambda \gg \rho_e, \rho_i$, with $\rho_e(\rho_i)$ being the electron (ion) gyroradius, and plasma microinstabilities ($\lambda \lesssim \rho_e, \rho_i$) have been invoked to account for high latitude ionospheric irregularities.

2.2.1 Plasma macroinstabilities

In the plasma fluid approximation the equations describing the basic dynamics of the electron and ion high latitude F region plasma can be written as follows: [Keskinen and Ossakow, 1982]

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\underline{v}_e) = 0 \tag{1}$$

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\underline{v}_i) = 0 \tag{2}$$

$$\underline{v}_e = \frac{cT_e}{B}\frac{\nabla_\perp n \times \hat{\underline{z}}}{n} + \frac{c\underline{E}_\perp \times \hat{\underline{z}}}{B} - \frac{\nu_{ei} c_s^2}{\Omega_e \Omega_i}\frac{\nabla_\perp n}{n} - \frac{e\underline{E}_z}{m\nu_{ei}} - \left(\frac{T_e}{m\nu_{ei}} + \frac{c_s^2}{\nu_{in}}\right)\frac{1}{n}\frac{\partial n}{\partial z}\hat{\underline{z}} + v_o \hat{\underline{z}} \tag{3}$$

$$\underline{v}_i = \frac{c\underline{E}_\perp \times \hat{\underline{z}}}{B} + \frac{\nu_{in}}{\Omega_i}\frac{c\underline{E}_\perp}{B} - \frac{cT_i}{eB}\frac{\nabla_\perp n \times \hat{\underline{z}}}{n} - \frac{\nu_{in} c T_i}{\Omega_i e B}\frac{\nabla_\perp n}{n} - \frac{\nu_{ei} c_s^2}{\Omega_e \Omega_i}\frac{\nabla_\perp n}{n} - \frac{\nu_{ei}}{\Omega_e}\frac{c_s^2}{\nu_{in}}\frac{1}{n}\frac{\partial n}{\partial z}\hat{\underline{z}} + V_o \hat{\underline{z}} \tag{4}$$

$$\nabla \cdot \underline{J} = 0 \tag{5}$$

Here n_α (α = i or e) is the species density and $\underline{E}$ is the total electric field. Since we will be interested in low frequencies and long wavelenghts, we have ignored inertial terms in the electron and ion momentum equations (3) and (4). Equation (5) results from the assumption of quasi-neutral fluctuations $n_e \simeq n_i = n$. In addition v_o and V_o refer to the electron and ion velocities along the magnetic field giving rise to a cold magnetic field aligned current. The symbol ν_{in} denotes the ion-neutral collision frequency, ν_{ei} the electron-ion collision frequency, c the speed of light, $T_e \simeq T_i \equiv T$ the species temperature, c_s the ion acoustic speed, and $\Omega_i(\Omega_e)$ the ion (electron) gyrofrequency. We have neglected ν_{en} compared with ν_{ei} and taken $\nu_\alpha/\Omega_\alpha << 1$ for α = i, e (F region approximation).

The following geometry is used: the y axis is in the north-south direction, the x axis points west, and the z axis is downward along the magnetic field.

Any two equations (1),(2), and (5) provide a complete description of the problem. We will use the ion continuity equation (1) and (5). After separating the total electric field into an ambient and fluctuating part $\underline{E}_{\perp} = \underline{E}_o - \nabla_{\perp}\delta\psi$ and transforming to a frame drifting with velocity $\underline{V}_o = -(c/B)\ [\hat{\underline{z}} \times \underline{E}_o - (\nu_{in}/\Omega_i)\underline{E}_o]$ we can linearize (1) and (5) by separating $n = n_o(y) + \delta n$ with δn, $\delta\psi \propto \exp\ [i(k_x x + k_z z - \omega t)]$, $\omega = \omega_r + i\gamma$, $L^{-1} \equiv (1/n_o)(\partial n_o/\partial y)$. This gives a growth rate

$$\gamma = \left[-\frac{\nu_{ei}}{\Omega_e}\frac{1}{L}\left(\frac{\nu_{in}}{\Omega_i}\frac{cE_o}{B} - \theta V_d\right)\right] \div \left(\theta^2 + \frac{\nu_{in}}{\Omega_i}\frac{\nu_{ei}}{\Omega_e}\right) - D_{\perp}k_x^{\ 2} - D_{\parallel}k_z^{\ 2} \qquad (6)$$

where $\theta \equiv k_z/k_x$, $\underline{V}_d = \hat{\underline{z}}(v_o - V_o)$, $k_{\perp}^2 = k_x^2$, $k_{\perp}^2 >> k_z^2$, $D_{\perp} = (\nu_{ei}/\Omega_e\Omega_i)c_s^2$ and $D_{\parallel} = (c_s^2/\nu_{in})\{1 + [(\nu_{in}/\Omega_i)^2/((\nu_{ei}\nu_{in}/\Omega_e\Omega_i) + (k_z^2/k_{\perp}^2))]\}$. ($\parallel$ denotes along z).

The expression for the growth rate γ in (6) can be maximized as a function of $\theta = k_z/k_x$, a measure of field alignment, using $\partial\gamma/\partial\theta|_{\theta=\theta_m} = 0$ giving

$$\theta_m = \frac{\nu_{in}}{\Omega_i}\frac{cE_{ox}}{B\ V_d} \pm \left[\left(\frac{cE_{ox}}{B\ V_d}\right)^2 \left(\frac{\nu_{in}}{\Omega_i}\right)^2 + \left(\frac{\nu_{ei}\nu_{in}}{\Omega_e\Omega_i}\right)\right]^{1/2} \qquad (7)$$

Using typical diffuse auroral F region parameters $\nu_{in}/\Omega_i \simeq 10^{-4}$, $\nu_e/\Omega_e \simeq 10^{-4}$, $E_{ox} \simeq 10$ mV/m, $j_{\parallel} = n_o e V_d \simeq 1\ \mu A/m^2$, $B = 0.5$ G, $n_o \simeq 10^5\ cm^{-3}$, this gives $|\theta_m| \simeq 10^{-4}$, i.e., approximate field alignment. Inserting these parameters into (6) with $L \simeq 20$ km, $D_{\perp} \simeq 0.2\ m^2/s$, and $D_{\parallel} \simeq 10^8\ m^2/s$, we find that the fastest growing linear modes have growth times $\gamma_{max}^{-1} \simeq 10^2$ s.

Although there is only one growth rate γ as given by (6) it is convenient to discuss γ in two limits. If $k_z = 0$, then the growth rate $\gamma \simeq cE_o/BL$ ($\underline{E} \times \underline{B}$ gradient drift instability) while if $E_o = 0$, $\gamma_{max} \simeq (V_d/2L)(1 + \nu_{in}\ \Omega_e/\Omega_i\nu_e)^{-1/2}$ and results from the current convective instability. We now discuss these two instabilitiles.

It is well know that convecting ionospheric plasma clouds are unstable, under certain conditions, and can produce plasma irregularities through the $\underline{E} \times \underline{B}$ gradient drift instability. The $\underline{E} \times \underline{B}$ gradient drift instability [Simon, 1963; Linson and Workman, 1970] is a convective instability with its nonlinear evolution [Zabusky et al., 1973; Scannapieco et al., 1976] resembling the classical Rayleigh-Taylor instability [Chandrasekhar, 1960] which arises when a heavy fluid is supported by a lighter fluid. The basic $\underline{E}x\underline{B}$ instability mechanism can be understood by noting Figure 2. Here the horizontal line represents an unperturbed contour of electron density. In addition, the ambient background electric field $\underline{E}_o$ is in the y-direction, the ambient magnetic $\underline{B}_o$ in the z-direction, and the background density gradient points in the x-direction. Let the density be perturbed by a small amplitude sinusoidal perturbation with wavenumber $\underline{k}$ parallel to $\underline{E}_o$. In the F region, the ions drift to the right in the Pedersen direction relative to the electrons. This gives rise to space charges (+ and -) which in turn cause small scale electric fields $\underline{E}'$ alternating in direction as shown. The corresponding $\underline{E}' x \underline{B}_o$ drifts will then convect depleted regions upward (toward increasing density) and enhanced regions downward (toward decreasing density) with the result that they both appear to grow relative to the background density gradient - an unstable situation. In the previous configuration the $\underline{E} \times \underline{B}$ gradient drift instability can also arise with a neutral wind $\underline{U}$ blowing in the -x direction with no $\underline{E}_o$.

Using both analytical and numerical simulation techniques, Keskinen and Ossakow [1982a] have studied the linear stability and nonlinear evolution of large scale convecting plasma enhancements in the auroral F-region ionosphere. Their results indicate that convecting diffuse auroral plasma enhancements can be driven unstable through the $\underline{E}x\underline{B}$ gradient drift instability. This destabilization can both directly and indirectly generate plasma density and electric field irregularities and fluctuations with scale sizes of several hundred kilometers to tens of meters. These irregularities take the form of anisotropic striation-like structures (elongated in the north-south direction for equatorward convection) which can form on the order of half an hour under typical auroral conditions. Fig. 3 illustrates the model of the plasma enhancement used in the numerical simulations. In a plane nearly perpendicular to the geomagnetic field Fig. 4 displays the linear and nonlinear evolution of the $\underline{E}x\underline{B}$ instability in a convecting auroral F region plasma enhancement. Parameters were used that agree with the observations of Vickrey et al. [1980]. Fig. 4a shows the initial configuration of the ionization enhancement and includes a small 1% density perturbation. Fig. 4b illustrates the linear regime at t = 550 sec and shows unstable growth on the poleward side of the equatorward convecting plasma enhancement. Fig. 4c gives the structure of the plasma enhancement at t = 1000 sec. Finally, Fig. 4d displays the plasma enhancement at t = 1600 sec in the well-developed nonlinear regime where steepened and elongated striation-like structures are evident. These fingers or striations will be oriented in a direction dependent upon the local electric field magnitude and direction. These theoretical results are not inconsistent with recent experimental observations [Tsunoda and Vickrey, 1982], using the Chatanika radar, which indicate large neutral wind velocities ($\underline{E} \times \underline{B}$ gradient drift instability) and fingerlike structures collocated with large scale convecting plasma enhancements (see Fig. 5). Vickrey and Kelley [1982] have studied the role of classical diffusion and a conducting E layer in removing these irregularities once they are produced. In addition, Keskinen and Ossakow [1982a] found that the larger scale size irregularities (fingers) can cascade to smaller scale size structures through nonlinear mode coupling and two-step processes. Examples of the spatial power spectra of these irregularities in the north-south $P(k_y)$ and east-west $P(k_x)$ direction taken in the nonlinear regime of the simulations is shown in Fig. 6. These power spectra can be well represented by power laws of the form $P(k_x) \propto k_x^{-n_x}$. with $n_x \approx 2-2.5$ for $2\pi/k_x$ between 100 km and 3 km while in the north-south direction $P(k_y) \propto k_y^{-n_y}$ with $n_y \approx 2$ for $2\pi/k_y$ between 256 km and 3 km. This process of finger formation, elongation, and steepening is almost self-similar in character with similar morphologies and power spectra for scale sizes λ between 1 km and 100 m [Keskinen and Ossakow, 1982b]. Some observational evidence [Vickrey et al., 1980] indicates that these plasma enhancements are probably subjected to ambient auroral convection patterns. As a result, these enhancements could be a major source of F region ionospheric irregularities throughout the auroral zone and polar cap.

The $\underline{E}\times\underline{B}$ instability in large scale plasma enhancements results from a coupling between the convective electric field and a density gradient perpendicular to the magnetic field. However, the coupling of density gradients and magnetic field aligned currents can also lead to plasma instability through the current convective instability [Lehnert, 1958;

Kadomtsev and Nedospasov, 1960]. Ossakow and Chaturvedi [1979] showed that plasma enhancements can also be linearly unstable to the current convective instability in regions where the $\underline{E}\times\underline{B}$ gradient drift instability is stable, i.e., in regions where the local convection velocity and density gradient are in opposite directions. The basic physical mechanism responsible for the current convective instability is as follows (see Fig. 7): Let the magnetic field $\underline{B}_o$ and current $j_{o\parallel}$ be in the z-direction, an ambient electric field $\underline{E}_o$ with perpendicular component in the x-direction, and a density gradient in the y-direction. Consider a density perturbation with wavevector $\underline{k}$ as shown. The projection on $\underline{k}$ of the ion Pedersen drift caused by $\underline{E}_{o\perp}$ results in a drift that is stable to the $\underline{E}\times\underline{B}$ instability. However, the assumed direction of $\underline{j}_{o\parallel}$ implies a relative drift between ions and electrons (in the electron rest frame) is anti-parallel to $\underline{B}_o$. This motion projected on $\underline{k}$ gives space charges and subsequent electric fields $\underline{E}''$. If the particle motion projected on $\underline{k}$ is dominated by $j_{o\parallel}$ then the total perturbation space charge electric fields will be denoted by $\underline{E}'$. The corresponding $\underline{E}' \times \underline{B}_o$ drifts will then convect enhanced (depleted) regions out of (into) the figure which will appear to grow relative to the background density in direct analogy to the $\underline{E}\times\underline{B}$ gradient drift instability as outlined previously. The ratio of the linear growth rate of the $\underline{E} \times \underline{B}$ gradient drift instability versus the current convective instability can be written approximately $(2V_o/V_d)(1 + \Omega_e\nu_i/\Omega_i\nu_e)^{1/2} \simeq 2V_o/V_d \simeq 2V_o ne/j_{o\parallel}$ since $\Omega_e\nu_i/\ \Omega_i\nu_e$ is of order unity in the auroral F region. Here $V_o = cE_o/B$ is the convection speed across the magnetic field. As a result, for strong perpendicular electric fields and/or weak currents and ambient densities the $\underline{E}\times\underline{B}$ gradient drift instability will dominate and vice versa. The nonlinear evolution of the current convective instability in the auroral F region ionosphere was investigated by Keskinen et al. [1980]. The evolution and morphology of the plasma density irregularities generated by the current convective instability were similar to that of the $\underline{E}\times\underline{B}$ instability. Basically, the current convective instability saturates (stabilizes) nonlinearly by feeding energy from the linearly unstable waves to the linearly damped harmonics [Chaturvedi and Ossakow, 1979]. Recently, the current convective instability in the auroral ionosphere has been extended to include other effects, e.g., magnetic shear [Huba and Ossakow, 1980] and ion inertial and collisional effects [Chaturvedi and Ossakow, 1981].

Another source of free energy in the high latitude F region ionosphere is the magnetic field aligned current system. Drummond and Rosenbluth [1962] first outlined the theory of field aligned current driven ion cyclotron instabilities for a collisionless plasma (for $k_\perp \rho_i \gtrsim 1$). Kindel and Kennel [1971] applied this theory to the auroral zone on the topside ionosphere where the plasma is only weakly collisional. Chaturvedi [1976], by invoking the collisional ion cyclotron instability, has shown that strong field aligned currents in the auroral F region ionosphere can lead to irregularities with scale sizes of hundreds of meters perpendicular to the magnetic field ($k_\perp \rho_i < 1$). The basic mechanism is that a field aligned current can excite, owing to dissipative effects due to electron-neutral collisions, a growing ion cyclotron wave propagating nearly transverse to the geomagnetic field. Current velocities of several kilometers per second are needed to excite this instability.

Hudson and Kelley [1976] have demonstrated that a temperature gradient driven drift wave instability, which arises from collinear density and temperature gradients perpendicular to the magnetic field, might explain density irregularities with scale sizes of hundreds of meters observed at the equatorward edge of the ionospheric plasma trough.

Kelley and Kintner [1978] have argued that highly structured electric fields, presumably of magnetospheric origin commonly seen in the dayside winter high latitude ionosphere, might cause density irregularities with similar scale sizes through the mixing of flux tubes that have varying plasma density.

2.2.2. Plasma microinstabilities

Small scale irregularities with sizes on the order of and smaller than the ion gyroradius (~ 10 m in the auroral F region) can be generated very efficiently through various plasma instability processes. These small scale irregularities could probably be detected by most high latitude backscatter radars.

Plasma density gradients, both sharp and smooth, are a ubiquitous feature of the high latitude F region ionosphere. These density gradients can drive a variety of drift wave type plasma instabilities. If ρ_i is the ion Larmor radius and L the density gradient scale length, then, in an approximate sense, the following modes are expected to dominate in the following density gradient regimes [Mikhailovskii, 1974] $\rho_i/L < (m_e/m_i)^{1/2}$, universal drift mode; $(m_e/m_i)^{1/2} < \rho_i/L < (m_e/m_i)^{1/4}$, drift cyclotron mode; $(m_e/m_i)^{1/4} < \rho_i/L$, lower-hybrid-drift mode. The growth of these drift modes tends to maximize for wavelengths λ near the electron or ion Larmor radius. Basu [1978] has noted, using Ogo 6 satellite observations, a high correlation between small irregularity structures and high latitude sub-trough plasma density gradients and invoked drift waves to explain these fluctuations. Other sources of sharp density gradients in the high latitude F region can be found near auroral arcs and near large scale convecting plasma enhancements [Vickrey et al., 1980].

Another source of plasma free energy that could directly excite small and large scale irregularities in the high latitude F region ionosphere is velocity sheared plasma flows, e.g., near auroral arcs [Kelley and Carlson, 1971]. For unstable velocity sheared plasma flows perpendicular to a magnetic field, the growth is nonlocal and maximizes for irregularity wavenumbers k such that $kL_v \lesssim 1$ [Mikhailovskii, 1974] where L_v is the velocity shear gradient scale length. A local instability ($kL_v > 1$) can operate for velocity sheared plasma flow parallel to a magnetic field [Mikhailovskii, 1974]. Recently, Keskinen and Huba [1982], using kinetic theory, showed that velocity sheared electron flow parallel to the geomagnetic field near strong discrete auroral arcs might also be unstable and lead to centimeter sized small scale irregularities with scale sizes on the order of the electron gyroradius.

Velocity space instabilities, as opposed to the previously discussed configuration space instabilities, have also been invoked to explain high latitude F region small scale irregularities. Ott and Farley [1975] have found that the action of ion-neutral charge exchange collisions can lead to anisotropic F region ion velocity distributions under the influence of large $\underline{E}\times\underline{B}$ convection velocities. They showed that such distributions are unstable to the Post-Rosenbluth instability [Rosenbluth and Post, 1965; Post and Rosenbluth, 1965] which is a short wavelength ($k \gg \Omega_i/v_d$), high frequency ($\omega \gg \Omega_i$) instability in which $\underline{k}$ is nearly perpendicular to $\underline{B}_o$. Here k, ω, Ω_i, v_d are the wavenumber, frequency, ion cyclotron frequency, and $\underline{E}\times\underline{B}$ drift speed, respectively. They showed that this instability would be excited at short wavelengths (10-20 cm) and argued that it might lead to density fluctuations of a few percent.

2.3 Structure from neutral fluid dynamics

Since the high latitude ionosphere is a coupled medium consisting of both plasma and neutral constituents, various plasma processes and irregularities could be transferred to the neutral gas via collisional effects and vice versa. Using the Chatanika radar, several studies [Baron, 1972; see recent review by Hunsucker, 1982 and references therein] have shown that the high latitude ionosphere often exhibits quasi-periodic fluctuations in electron density and temperature with these fluctuations having large equatorward velocities. It is generally accepted [Hunsucker, 1982] that these traveling ionospheric disturbances (TID's) are ionospheric manifestations of atmospheric gravity waves [Hines, 1960]. The TID's are a very large scale phenomena with wavelengths of several hundred to thousands of kilometers. The most likely sources [Hunsucker, 1982] of the gravity waves/TID's are: (1) Joule heating and Lorentz forces associated with the auroral electrojet and (2) intense particle precipitation events. These large scale TID's could act to seed other macroscopic plasma instabilities. Much work remains to be done in this area.

3. HIGH LATITUDE E REGION IRREGULARITIES

In the high latitude E region, experimental observations using both radar backscatter [Harang and Stoffregen, 1938; Bowles, 1955; McNamara, 1955; Balsley and Ecklund, 1972 see reviews by Hultqvist and Egeland (1964), Lange-Hesse (1967), Unwin and Baggaley, (1972) Greenwald (1979), Fejer and Kelley (1980)] and rocket techniques [Kelley and Mozer, 1973; Holtet, 1973; Olesen et al., 1976; Ogawa et al., 1976] have shown the existence of plasma density irregularities with scale sizes of meters to hundreds of meters. These irregularities have been shown to be highly correlated with the auroral electrojet [Greenwald et al., 1975b; Tsunoda et al., 1976a]. Various plasma instabilities and processes have been successful in accounting for many of the features of these irregularities.

Fluid equations that can describe the basic dynamics of the auroral E region electrojet plasma can be written [Rogister and D'Angelo, 1970; Sudan et al. 1973]

$$\frac{\partial n_e}{\partial t} + \nabla \cdot n_e \underline{V}_e = 0 \tag{8}$$

$$\frac{e}{m_e}\left(\underline{E} + \frac{\underline{V}_e \times \underline{B}}{c}\right) + \frac{T_e}{m_e}\frac{\nabla n_e}{n_e} + \nu_e \underline{V}_e = 0 \tag{9}$$

$$\frac{\partial n_i}{\partial t} + \nabla \cdot n_i \underline{v}_i = 0 \tag{10}$$

$$\left(\frac{\partial}{\partial t} + \underline{v}_i \cdot \nabla\right) \underline{v}_i = -\frac{T_i}{m_i}\frac{\nabla n_i}{n_i} + \frac{e}{m_i}\underline{E} - \nu_i \underline{v}_i \tag{11}$$

$$n_e = n_i = n \tag{12}$$

where $\underline{E} = -\nabla\psi$ and n_α, $\underline{v}_\alpha$, ν_α, m_α, T_α are ($\alpha = e,i$) the density, velocity, collision frequency with neutrals, mass, and temperature, respectively. In addition, ψ is the electrostatic potential, $\underline{E}$ the electric field, c the speed of light and $\underline{B}$ the magnetic field. Equations (8) - (12) are valid under the assumptions of electrostatic waves, charge neutrality $n_e \simeq n_i$, isothermal electrons and ions, and neglect of electron inertia. Taking $\underline{B} = B_o\hat{\underline{x}}$, $\underline{E} = e_o\hat{\underline{x}} - \nabla\delta\psi$ linearizing eq. (7) - (12) with δn_i, $\delta\psi \propto \exp[(\underline{k} \cdot \underline{x} - \omega t)]$ and assuming a relative drift $\underline{V}_d$ between electrons and ions across the magnetic field, we find the frequency and growth rate of waves propagating perpendicular to the magnetic field:

$$\omega_{\underline{k}} = \underline{k} \cdot \underline{V}_d/(1 + \psi) \tag{13}$$

$$\gamma_{\underline{k}} \; (\psi/1+\psi)[(\Omega_e/\nu_e)(\omega_{\underline{k}}/kL) + (\omega_k{}^2 - k^2c_s{}^2)/\nu_i] \tag{14}$$

where $\psi = \nu_i\nu_e/\Omega_i\Omega_e$, $L = |n_o/\nabla n_o|$ with ∇n_o the electron density gradient along $\underline{E}_o$, and $C_s = [(K(T_e + T_i)/m_i]^{1/2}$ the ion acoustic velocity. Although (13) and (14) describe only one instability, it is convenient to discuss two well known limits. If $L \to \infty$ (no density gradient) then (13) and (14) reduce to the Farley-Buneman instability [Farley, 1963; Buneman, 1963] with instability threshold condition $V_d > c_s$. If $V_d \ll c_s$ and $(\Omega_e/\nu_e)(\nu_i/\Omega_k)(1/kL) > 1$ then the $\omega_k{}^2$ term in (14) can be neglected recovering the $\underline{E} \times \underline{B}$ gradient drift (cross field) instability [Simon, 1963] with approximate instability criterion $(\Omega_e/\nu_e)(V_d/L) > (k^2c_s{}^2/\nu_i)$ when $\underline{k}$ is along the y direction.

Radar backscatter studies have provided much information regarding small scale irregularities (with meter-sized wavelengths) in the high latitude E region. The E region radar echoes, which are highly aspect sensitive, can only be observed at large angles to the electrojet current due to geometric considerations. Basically, the echoes can be divided into two types depending upon their duration and latitudinal and longitudinal extent. Additional characteristics such as location, threshold, doppler feature, etc. have been summarized previously [Hultqvist and Egeland, 1964; Lange-Hesse, 1967; Unwin and Baggeley, 1972; Greenwald, 1979; Fejer and Kelley, 1980]. The Farley-Buneman (two-stream) instability, which is driven by the electrojet current, has been invoked to explain the small scale irregularities in the auroral and polar cap E region ionosphere [Olesen, 1972; Moorcroft, 1972; Wang and Tsunoda, 1975; Olesen et al., 1975, 1976; Primdahl et al., 1974]. The linear theory of the Farley-Buneman instability seems to explain several features of small scale irregularities in the high latitude E region especially in the polar cap, e.g., peak backscatter and electric field fluctuations in the direction of the current [Olesen et al., 1976; Tsunoda et al., 1976a; Bahnsen et al. 1978]. However, several irregularity characteristics cannot be explained using linear theory, e.g., waves propagating with small and large aspect angles perpendicular to the electrojet current, wave phase velocity in excess of the ion sound speed, saturated wave amplitudes and spectra, and electron heating. Several nonlinear saturation theories of the Farley-Buneman instability have been proposed, e.g., quasilinear effects [Sato, 1972; Rogister, 1971], resonance broadening [Weinstock and Sleeper, 1972], mode coupling [Rogister and Jamin, 1975], and stabilization by external low frequency E x B turbulence [Keskinen, 1981]. These nonlinear theories predict different saturated wave amplitudes and steady state spectra. To explain the large aspect angle waves Hofstee and Forsyth [1972] and Moorcroft [1972] have suggested an ambient magnetic field distortion caused by large electrojet currents while Volosevich and Liperovsky [1975] argued for ion acoustic waves generated by E region field aligned currents. Recently, St.-Maurice et al. [1981] and Schlegel and St.-Maurice [1981] have shown that anomalous electron temperatures in the high latitude E region can be quantitatively explained in terms of plasma heating caused by unstable Farley-Buneman waves (see Fig. 18). Good agreement is made between theory and observations. Finally, D'Angelo [1973] has proposed the ion cyclotron instability, as generated by field aligned currents in the high latitude E region, to be another source of both large and small scale irregularities. D'Angelo notes that the ion cyclotron wave excitation would probably take place at altitudes higher than those of the auroral elctrojet current and, subsequently, propagate downward at an aspect angle on the order of 10%.

Larger scale irregularities in the high latitude E region with wavelengths up to several hundreds of meters have been identified principally through in situ rocket probes [Kelley and Mozer, 1973; Holtet, 1973; Ogawa et al., 1976]. Vertical density gradients are often observed in conjunction with auroral electrojet currents. As a result, the ExB gradient drift instability has been invoked [Greenwald, 1974, 1975a] to explain the large scale irregularities. This instability is different from the ExB instability used to describe high latitude F region irregularities (see Section 2). In the F region case, the basic current flow is in the Pedersen direction while the Hall current dominates in the E region. However, the physical mechanisms describing the ExB instability in both regions are essentially identical. Again, the linear theory of the ExB instability cannot account for irregularities propagating perpendicular to the electrojet current and saturated wave amplitudes and spectra. Several nonlinear theories of the E-region gradient drift instability, e.g., quasilinear effects [Sato and Ogawa, 1976], resonance broadening [Weinstock and Williams 1971] and strongly turbulent nonlinear wave-wave interactions [Sudan and Keskinen, 1977] have been proposed. Greenwald [1974] has attempted to account for small scale oblique waves by appealing to a two-step multilinear process [Sudan et al., 1973] in which secondary vertical short wavelength waves can grow at the expense of the perturbation electric fields and density gradients associated with the linearly unstable primary horizontal longer wavelength gradient drift fluctuations. Greenwald's analysis shows that secondary gradient-drift waves can be excited while there is difficulty in generating secondary Farley-Buneman waves. Radar echoes resembling secondary Farley-Buneman modes have been observed [Moorcroft and Tsunoda, 1978; Moorcroft, 1979].

4. SUMMARY

We have attempted to give an overview of theoretical interpretations of naturally occurring high latitude E and F region ionospheric irregularities. Much quantitative progress has been made in recent years in identifying the source mechanisms of high latitude irregularities. Plasma instabilities have been shown to play an important role in the generation and evolution of these irregularities.

In the auroral F region, there is some evidence for large scale ($\lambda > 10$ km) structure and irregularities being produced by particle precipitation events and subsequent formation of large scale size plasma enhancements. Some experimental observations indicate that these plasma enhancements appear to follow ambient auroral convection patterns. These convecting plasma enhancements have been shown to be unstable to plasma macroinstabilities, i.e., the $\underline{E}\times\underline{B}$ and current-convective instability, which can generate irregularities and structure with scale sizes on the order of and smaller than the approximate size of the plasma enhancements. Nonlinear wave-wave interactions and associated wavenumber cascades can lead to further structuring until diffusive-like processes dominate and irregularity formation is quenched. Since these plasma macroinstabilities become highly nonlinear further progress in this area can only be made through numerical modeling and simulations of the fundamental plasma equations. Moreover, since the convective motions can be spatially dependent (e.g., $\underline{E}$ can be a function of space) and so introduce velocity shear, it is important to assess the influence of this velocity shear on the plasma macroinstabilities (see for example Guzdar et al., 1982; Huba et al., 1982). This would also include being able to model this shear in the nonlinear numerical simulations. In addition, the role of neutral fluid disturbances, i.e., gravity waves, in producing large scale irregularities should be further investigated. These waves could act to "seed" large scale plasma macroinstabilities. The generation of smaller scale irregularities with the wavelengths of meters to tens of meters in the auroral F region has been given considerably less theoretical attention. Free energy sources for these smaller scale structures include sharp density gradients (leading to drift waves), velocity sheared plasma flows both parallel and perpendicular to the magnetic field, and anisotropic plasma velocity distributions. An outstanding question is the saturated amplitudes and spectra of the small scale irregularities and the role they play in influencing larger scale irregularities and structures.

In the high latitude E region, the strong electrojet currents across the geomagnetic field have been shown to drive plasma instabilities, i.e., the Farley-Buneman and $\underline{E}x\underline{B}$ instabilities, which can lead to both small and large scale irregularities. The linear theories of these instabilities can explain several features of the irregularities. Results from nonlinear studies e.g., saturated amplitudes, of these instabilities are conflicting in several respects. Further analytical and numerical studies of these instabilities especially the Farley-Buneman (two-stream) instability are needed.

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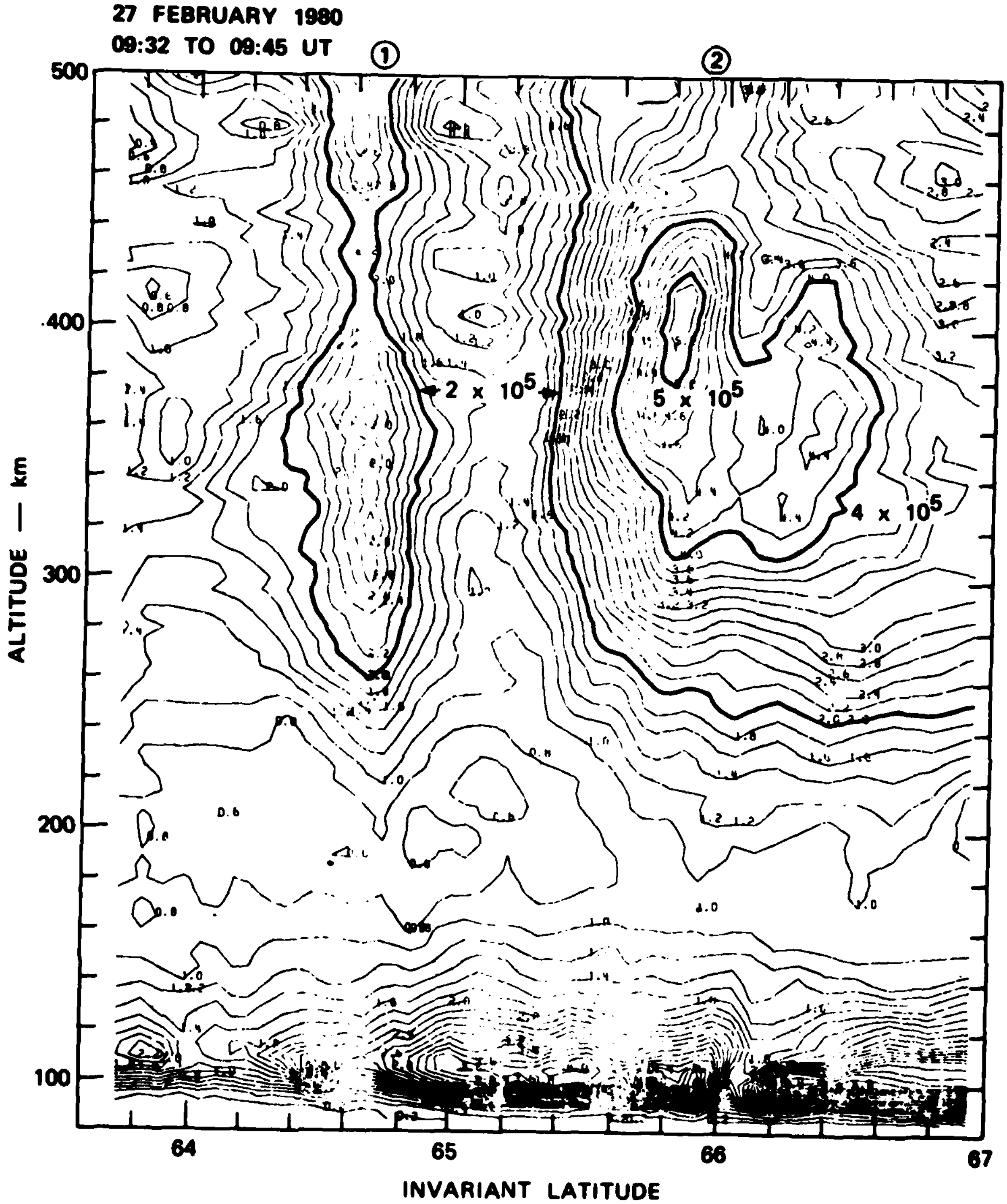


Fig. 1 — Altitude/latitude variation of electron density on 27 February 1980, from 0932 to 0945 UT [from Vickrey et al., 1980]

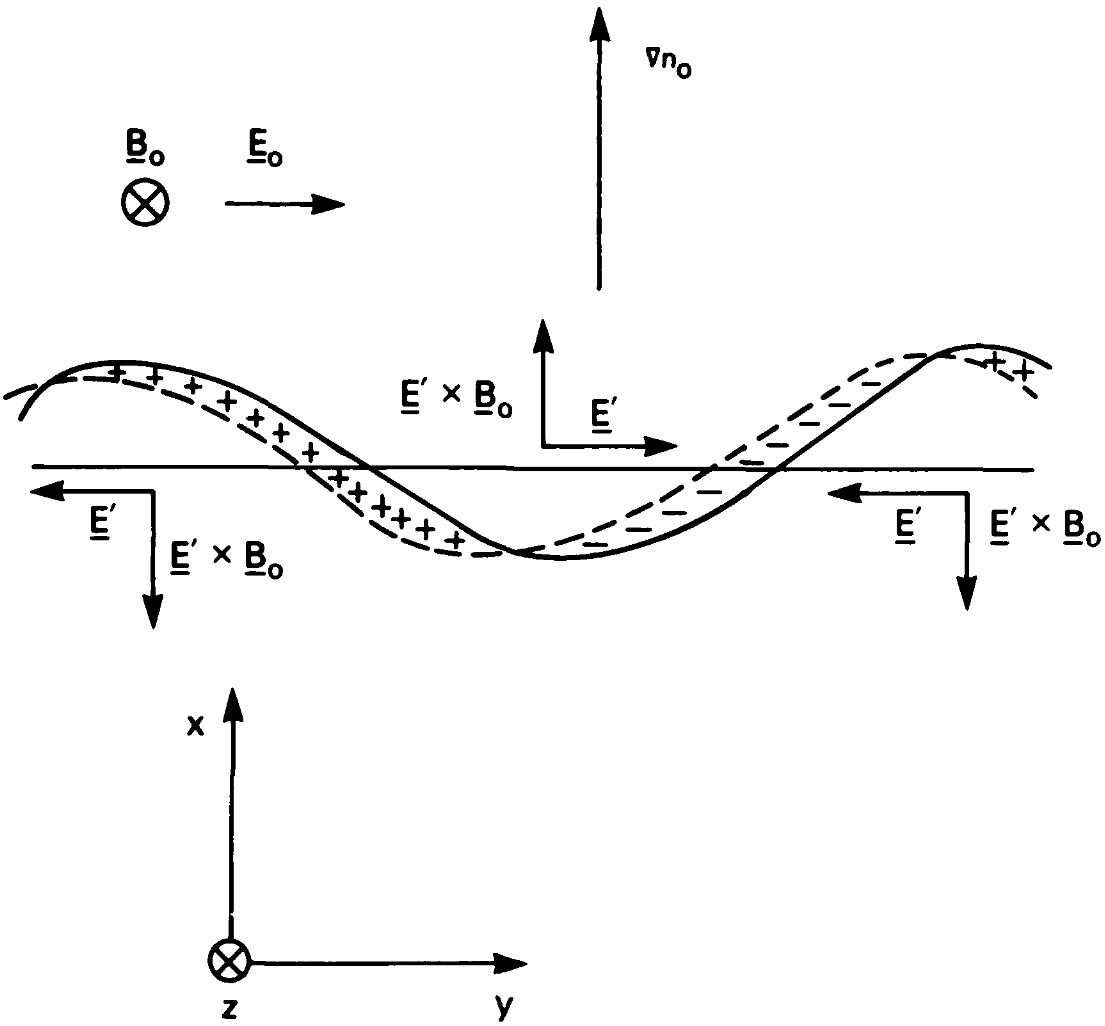


Fig. 2 — Physical mechanism of F region ExB gradient drift instability

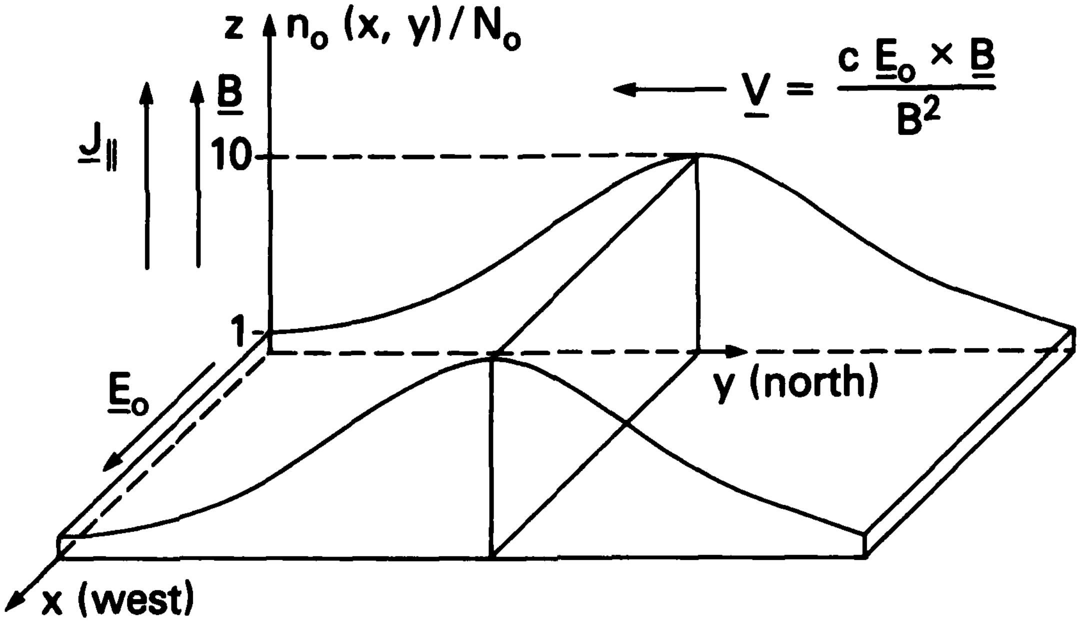
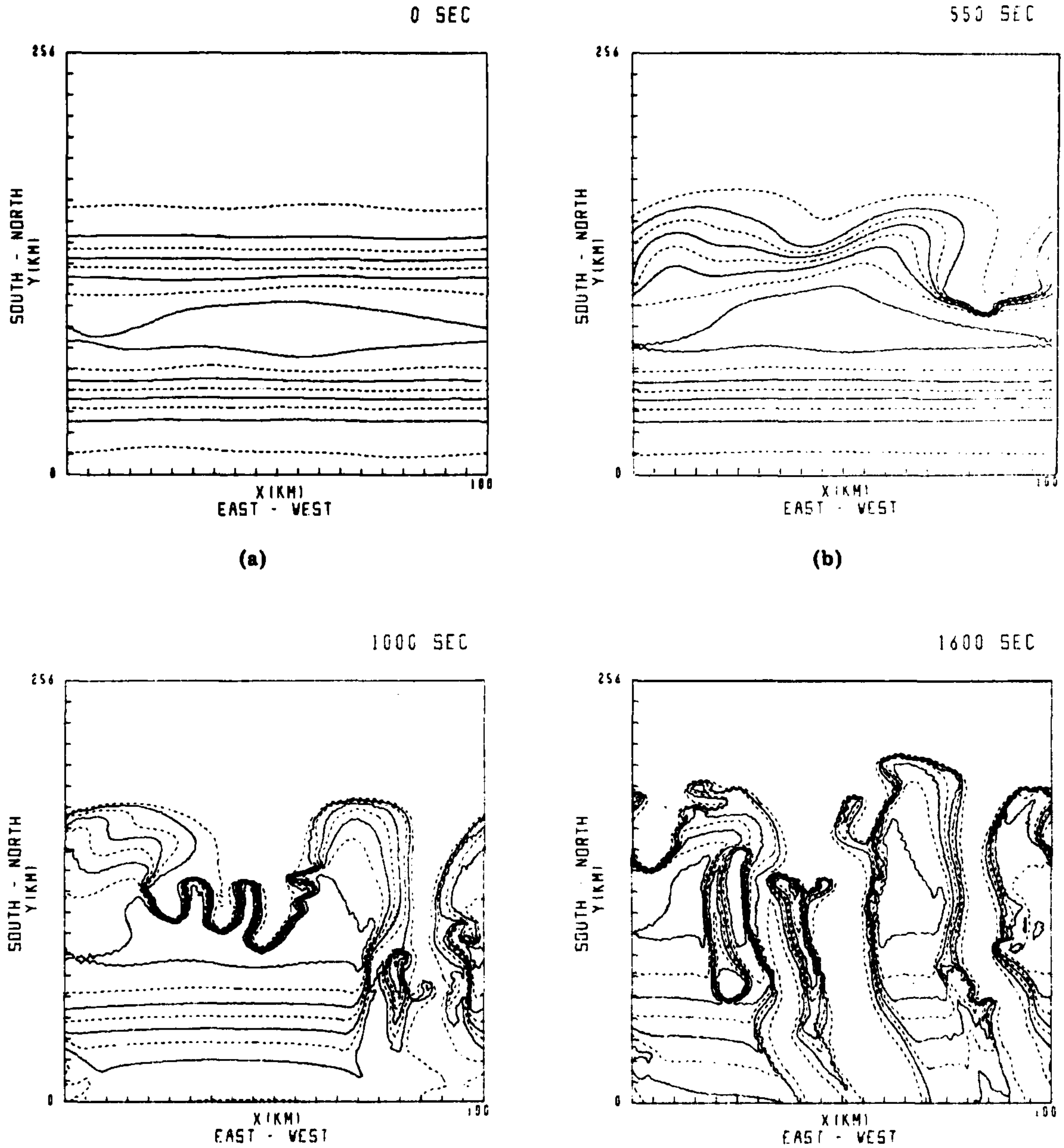


Fig. 3 — Model of plasma enhancement used in numerical simulations [Keskinen and Ossakow, 1982]. The quantity $n_O(x,y)$ represents the initial plasma enhancement density profile while N_O is the average background auroral F region plasma density.



(a) (b) (c) (d)

Fig. 4 — Real space plasma isodensity contour plots of $[n_0(x,y) + \delta n(x,y)]/N_0$ at (a) t = 0 sec, (b) t = 550 sec, (c) t = 1000 sec, (d) t = 1600 sec. The y-axis is compressed by a factor of 2.58. The distance between tick marks in the x direction (y direction) is 5 km (12.8 km). Eight contours are plotted in equal increments of 1.25 beginning at 1.25. The observer is looking upward along the magnetic field lines [figure from Keskinen and Ossakow, 1982].

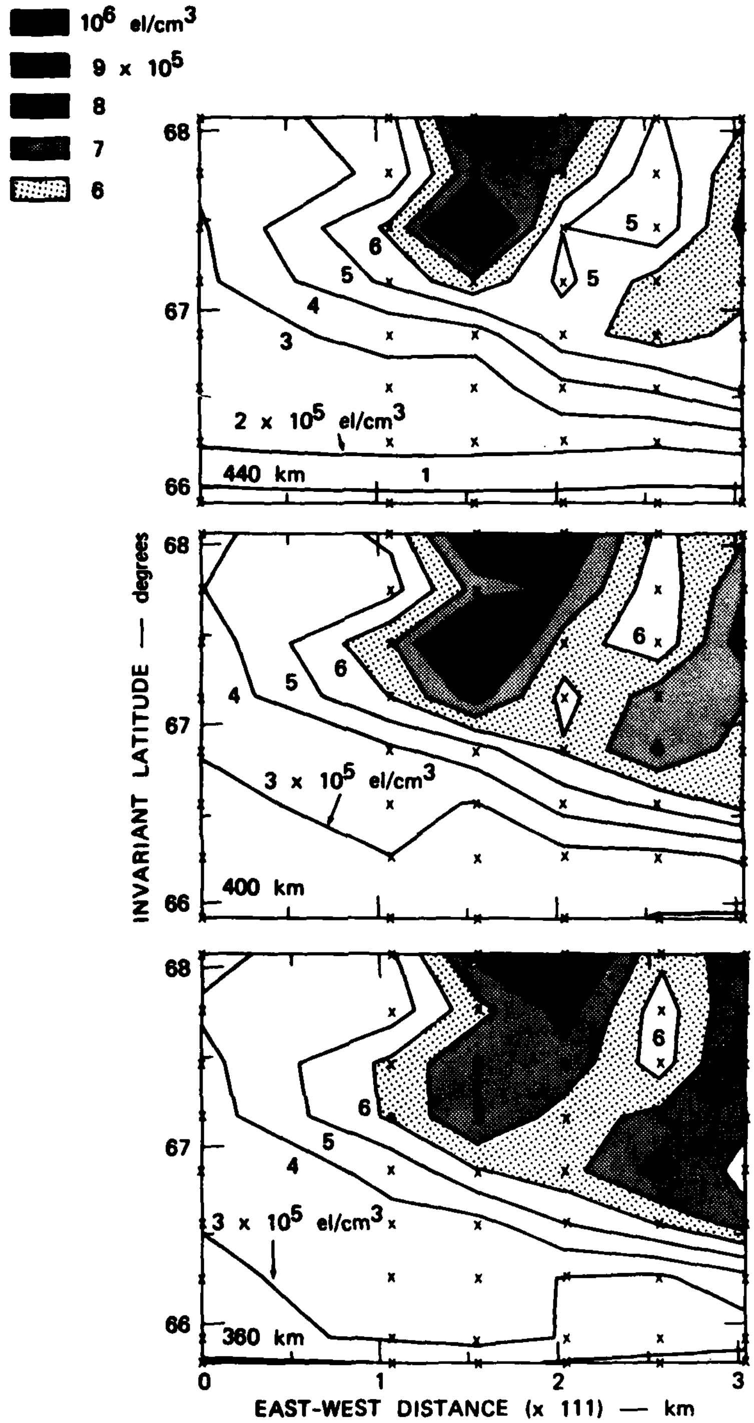
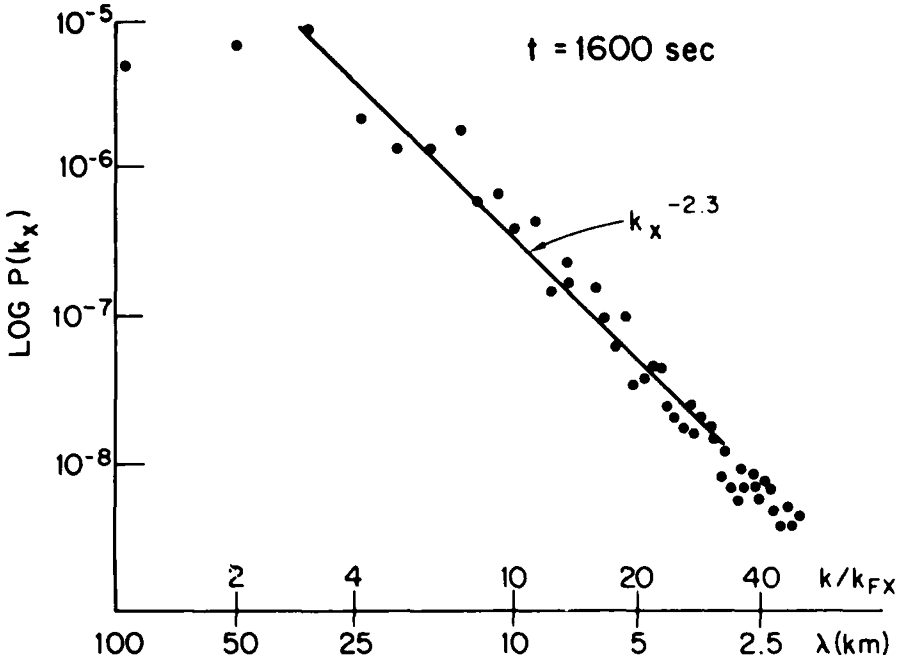
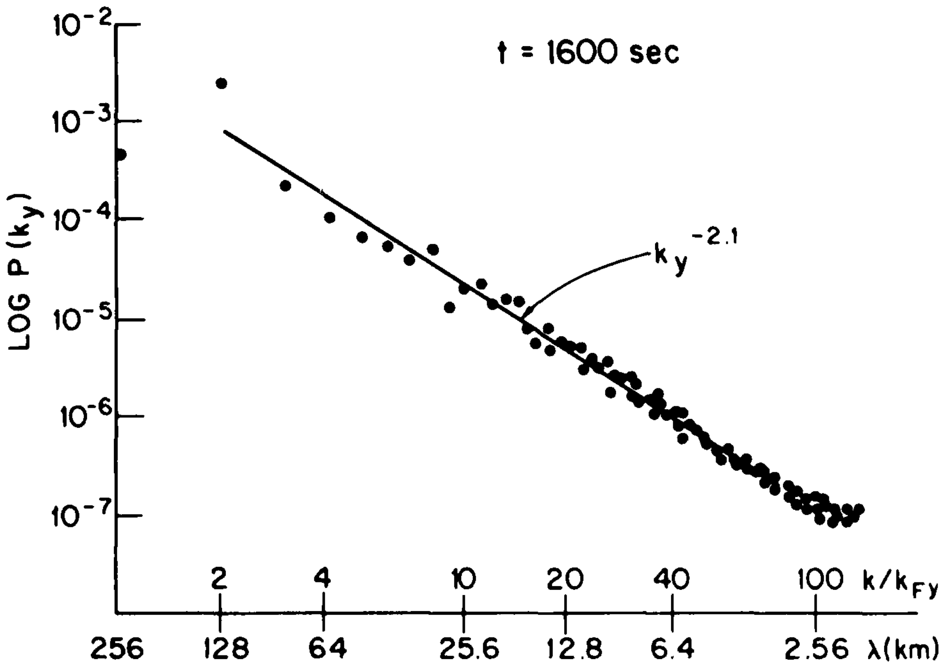


Fig. 5 — East-west structure/latitude variation of electron density at three different altitudes on 16 November, 1ʼ [from Tsunoda and Vickrey, 1982]



(a)



(b)

Fig. 6 — One dimensional (a) x power spectra $P(k_x)$ and (b) y power spectra $P(k_y)$ at t = 1600 sec. In (a) $k_{Fx} = (2\pi/100)\ km^{-1}$ while in (b) $k_{Fy} = (2\pi/256)\ km^{-1}$. The circles represent the numerical simulation results; the solid curve is a least squares fit. The units of $P(k_x)$, $P(k_y)$ are kilometers [figure from Keskinen and Ossakow, 1982].

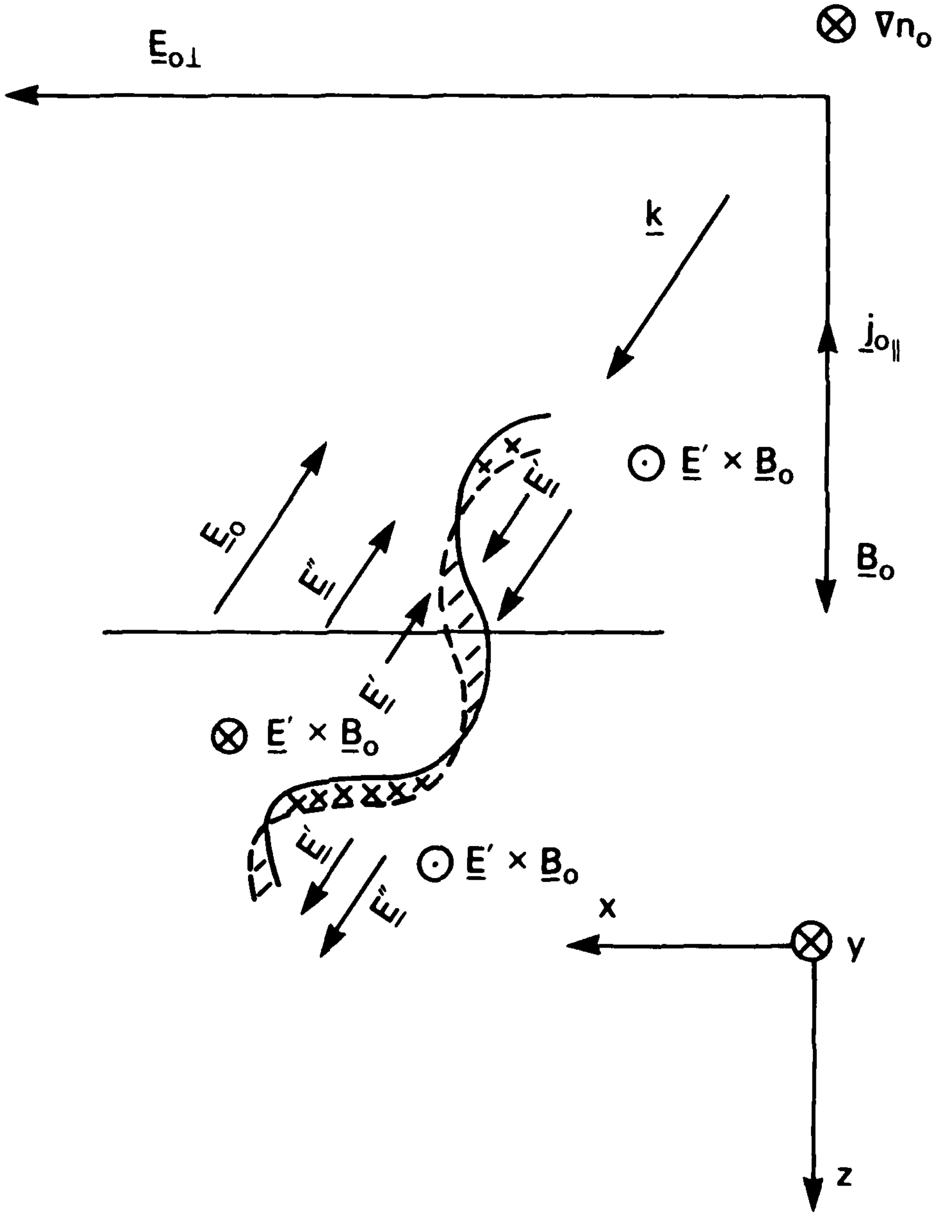


Fig. 7 -- Physical mechanism of the current convective instability [from Ossakow and Chaturvedi, 1979]

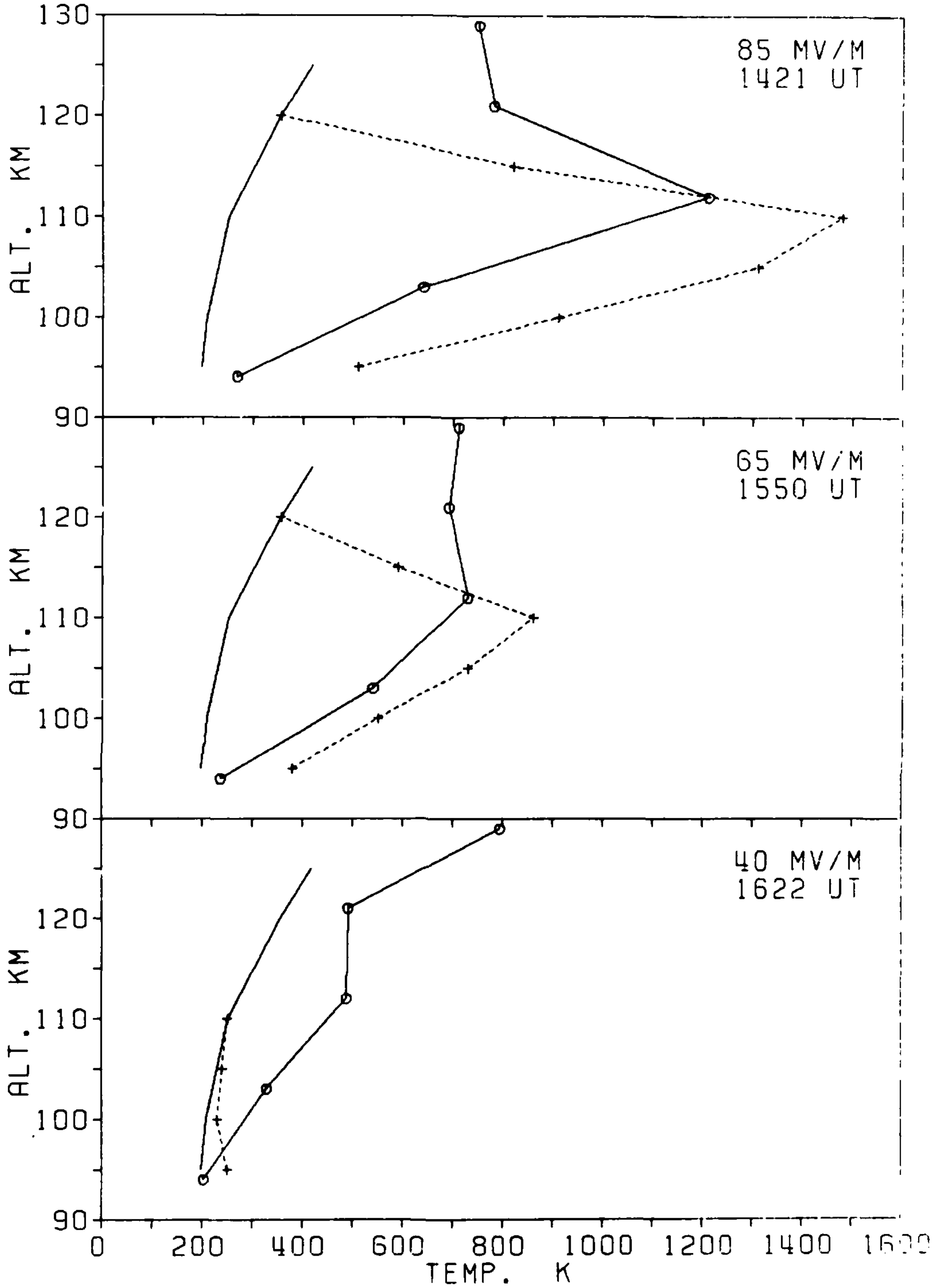


Fig. 8 — Measured electron temperature profile (T_e^m, solid line) and corresponding electron temperature profile obtained from the quasilinear theory (T_e^{th}, dashed line) for three different electric fields (85) mV/m, upper panel; 65 mV/m, middle panel; and 40 mV/m, lower panel). The CRA neutral temperature T_n has also been plotted for comparison [from St.-Maurice et al., 1981].

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