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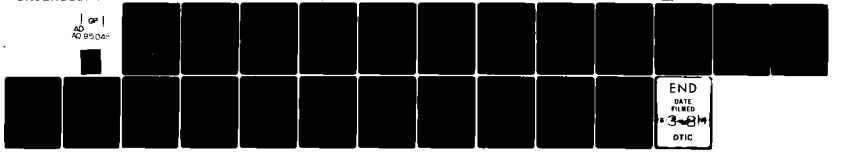

NRL Memorandum Report 4432

Physical Mechanism of the Lower-Hybrid-Drift Instability in a Collisional Plasma

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We present a physical discussion of the lower-hybrid-drift instability in both collisionless and collisional plasmas. The instability is important since it is the most promising explanation of small-scale irregularities (i.e., ≲ 1m) observed during equatorial spread F.

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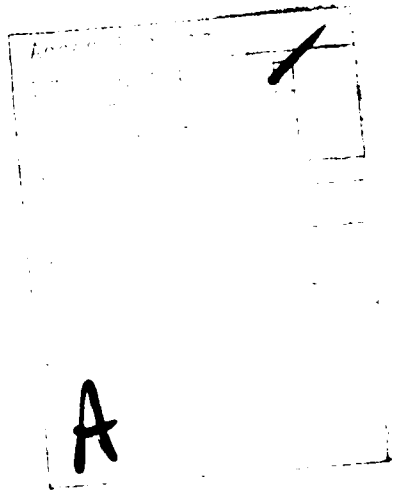

PHYSICAL MECHANISM OF THE LOWER-HYBRID-DRIFT INSTABILITY IN A COLLISIONAL PLASMA

I. INTRODUCTION

During the past several years, high-frequency radar backscatter experiments have revealed a spectrum of short-wavelength (i.e., below the ion gyroradius) irregularities during equatorial spread F (ESF). Radar backscatter observations at 50 MHz, 155 MHz and 415 MHz indicate density fluctuations exist with scale sizes of 3m, 1m, and 36 cm, respectively [FARLEY et al., 1970; WOODMAN and LAHOZ, 1976; COSTA and KELLEY, 1978a,b; HUBA et al., 1978]. Most recently, TSUNODA (1980) has observed radar backscatter from 11 cm (1320 MHz) irregularities during equatorial spread F at high altitudes, using the TRADEX radar. These observations were part of a coordinated Defense Nuclear Agency campaign at Kwajalein to study ionospheric irregularities during equatorial spread F. Sharp density gradients were observed during this campaign (M. C. KELLEY, private communication, 1980) and have been observed during past equatorial spread F events (COSTA and KELLEY, 1978a,b). The scale lengths of these gradients range from tens of meters to several hundred meters and are presumably due to primary longer wavelength instabilities such as the Rayleigh-Taylor instability. Since the typical ion gyroradius is $r_{Li} \sim 5$m, it is found that $r_{Li}/L_n \lesssim 0.2$ where L_n is the density gradient scale length.

Based upon the above evidence, it has been suggested that various drift instabilities are responsible for the short wavelength irregularities [HUBA et al., 1978; COSTA and KELLEY, 1978a,b; HUBA and OSSAKOW, 1978a,b], depending upon the wavelength observed. Although collisionless drift waves would easily be excited under these circumstances, collisional effects play an important role in the instabilities investigated thus far [HUBA and OSSAKOW, 1979a,b; SPERLING and GOLDMAN, 1980]. Specifically, the lower-hybrid-drift instability is the prime candidate to explain the 1m, 36 cm and

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11 cm irregularities. Recent research has indicated that ion collisions (i.e., ion-ion) are necessary for the destabilization of the mode during equatorial spread F [HUBA et al., 1978; HUBA and OSSAKOW, 1979a]. On the other hand, electron collisions (i.e., electron-ion, electron-electron, electron-neutral) are a stabilizing influence and place a threshold condition on the gradient scale length necessary to excite the instability [HUBA and OSSAKOW, 1979a, 1980; SPERLING and GOLDMAN, 1980]. The analysis of these collisional effects are fairly complex and, to some degree, obscure the underlying physics involved. The purpose of this paper is to present a simple discussion of the lower-hybrid-drift instability which elucidates the physical mechanism of the mode and the effects of collisions. For pedagogical purposes we consider an over-simplified model of the ionospheric plasma. Thus, the results presented (e.g., growth rates, threshold conditions) are not quantitatively accurate but are of a "back-of-the envelope" nature.

II. THEORY

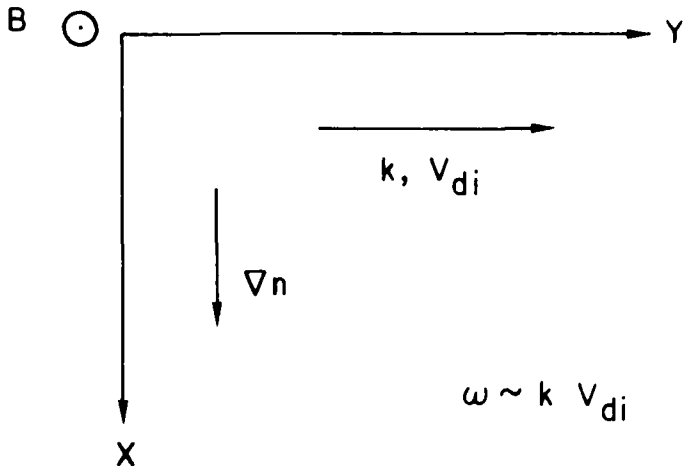
A. Equilibrium and Assumptions

We consider a plasma immersed in a homogeneous, unidirectional magnetic field $B = Be_z$ with an inhomogeneous density profile $n = n_o(x)$ as shown in Fig. 1a. For simplicity we choose T_i = constant and $T_e = 0$. The influence of finite electron temperature effects is discussed in Section III. The equilibrium drift is $V = V_{di}\, e_y$ where $V_{di} = (cT_i/eB)\, \partial n_o/\partial x$ is the ion diamagnetic drift velocity. This drift provides the free energy to drive the instability. We point out that $V_{di} \ll v_i$ for ionospheric spread F conditions (here, v_i is the ion thermal velocity). Collisions are neglected in the equilibrium configuration since we are interested in time scales much shorter than the diffusion time. In the stability analysis we assume that perturbed quantities vary as $\exp[i(ky - \omega t)]$. That is, we consider flute perturbations so that $\underline{k} \cdot \underline{B} = 0$. We consider electrostatic oscillations since $\beta \ll 1$ and make use of the local approximation which requires $k L_n \gg 1$ where $L_n = (\partial n_o/\partial x)^{-1}$. Also, we assume that $\omega \ll \Omega_e$ so the electrons are strongly magnetized. Finally, we assume that the ions behave as unmagnetized particles which is crucial to the instability. The ions have an equilibrium distribution function which can be described by

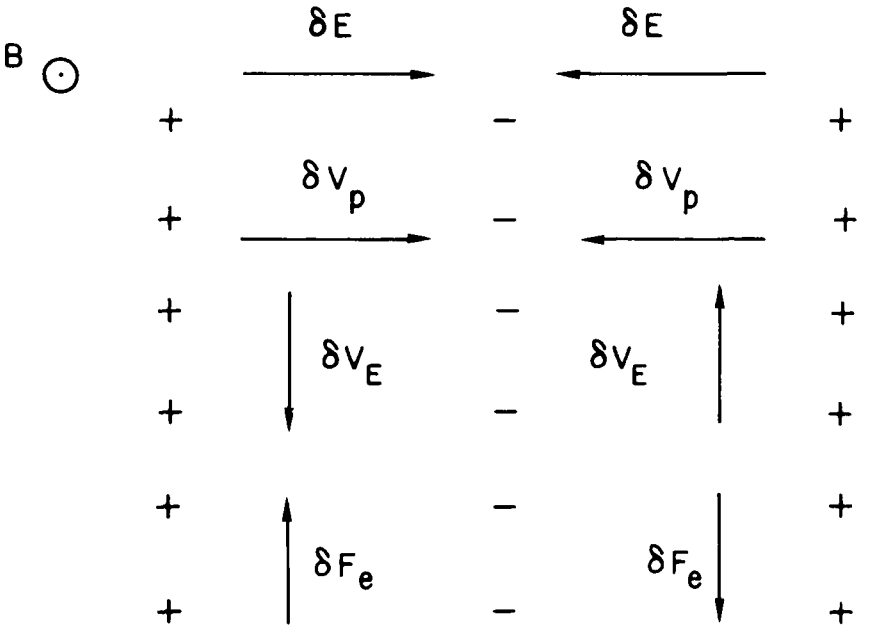
$$F_{io} = \left(\frac{1}{\pi v_i^2}\right)^{3/2} \exp\left[-(v_x^2 + (v_y - V_{di})^2 + v_z^2)/v_i^2\right] \tag{1}$$

B. Collisionless Plasma

It is worthwhile to first discuss the physics of the lower-hybrid-drift instability in collisionless plasmas before introducing collisional effects. The assumption of unmagnetized ions is justifiable for time scales



(1a)



(1b)

Fig. 1 — Equilibrium and electron dynamics in the wave field. (1a) Slab geometry and equilibrium configuration. (1b) Electron motion in the wave field δE. Here, δV_E is the ExB drift, δV_p is the polarization drift and δF_e is the force on electrons due to collisions.

much smaller than an ion gyroperiod (i.e., $\tau \ll \tau_i$ where $\omega = \omega_r + i\gamma$ and τ_i is the ion cyclotron period). Thus, the ions have straight line orbits on this time scale. Moreover, we consider waves such that $\omega \gg kv_i$ so that the ions are adiabatic (i.e., $\delta n_i/n_o \sim -e\phi/T_i$). The electrons, on the other hand, are strongly magnetized and execute an oscillatory $E\times B$ drift ($\delta V_E = c\delta E/B$) and a polarization drift ($\delta V_p = (c/B\omega_{ce})\partial\delta E/\partial t$) as shown in Fig. 1b. The above equilibrium gives rise to a drift wave

$$\omega = kV_{di}/(1 + k^2\rho_{es}^2) \tag{2}$$

which propagates across the magnetic field in the direction of the ion diamagnetic drift (where $\rho_{es}^2 = (T_i/m_e)/\omega_{ce}^2$).

This drift wave can become unstable because of inverse ion Landau damping. That is, the wave can absorb energy from a group of ions moving in phase with the wave. This can be seen by noting that

$$\dot{W}_w + \dot{W}_p = 0 \tag{3}$$

where $\dot{W}_w$ and $\dot{W}_p$ are the time rates of change of the wave energy density and particle energy density, respectively. Now,

$$\dot{W}_w = \gamma\,\delta E^2 \tag{4}$$

and

$$\dot{W}_p = \dot{W}_{pi} = -\left(v_y \frac{\partial F_{io}}{\partial v_y}\right)_{v_y = \frac{\omega}{k}} \delta E^2 \tag{5}$$

so that

$$\gamma = \left(v_y \frac{\partial F_{io}}{\partial v_y}\right)_{v_y = \frac{\omega}{k}} \tag{6}$$

Since $\partial F_{io}/\partial v_y > 0$ for $\omega < k V_{di}$ (from Eqs. (1) and (2)) we obtain a positive growth rate (i.e., $\gamma > 0$). The growth rate is given by

$$\gamma = kV_{di} \frac{V_{di}}{v_i} \frac{k^2\rho_{es}^2}{(1+k^2\rho_{es}^2)^2} \qquad (7)$$

Note that for $k^2\rho_{es}^2 << 1$ that $\gamma \propto k^3$ while for $k^2\rho_{es}^2 >> 1$ that $\gamma \propto k^{-1}$. Growth is a maximum for $k\rho_{es} \sim 1$. Since we require $\omega > \nu_i$ for the ions to be unmagnetized, a threshold is placed on the diamagnetic drift (or density gradient scale length) which is roughly given by $V_{di}/v_i > (m_e/m_i)^{\frac{1}{2}}$ or $L_n/r_{Li} < (m_i/m_e)^{\frac{1}{4}}$ where r_{Li} is the mean ion Larmor radius.

C. Collisional Plasma

1. Ion Collisions (ion-ion)

As just noted, a threshold condition exists on the density gradient scale length to excite the mode in collisionless plasmas. For ionospheric dontions, the threshold is approximately $L_n > 30m$ which represents a very sharp density gradient. Such sharp gradients are rarely observed [COSTA AND KELLEY, 1978a]. Superficially, this would appear to limit the applicability of this mode to spread F; however, the role of ion-ion collisions alters the threshold condition. In the spirit of the paper, we simply describe how ion-ion collisions influence the instability rather than present a mathematical analysis. A detailed derivation can be found elsewhere (BOBA and OSSAKOW, 1979a).

In order to excite the instability ions must be in resonance with a drift wave propagating perpendicular to the magnetic. Clearly if the ions are magnetized, they are tied to the field lines and cannot move across the field. However, ion-ion collisions provide a mechanism that allows ions to move across magnetic field lines. That is, ions can diffuse a distance

$L_D \sim (\nu_{ii}/\omega_i)^{\frac{1}{2}} r_{Li}$ in one wave period. If this distance is greater than a wavelength then the ion's cross-field behavior is lost and the ion behave as unmagnetized particles. The ion demagnetization condition is

$$\frac{\nu_{ii}}{\omega_i} k_\perp r_{Li} \sim 1 \tag{8}$$

Since maximum growth occurs for $k_\perp r_{Li} \sim 1$, we require $\nu_{ii}/\omega_i \sim m_e/m_i \sim 10^{-4}$ for instability to occur in an O^+ plasma. Equation (8) is easily satisfied for typical spread F conditions.

2. Electron Collisions (electron-ion, electron-neutral, electron-electron)

In collisionless plasmas, the only energy exchange occurs between the wave and the resonant ions since the electrons are nonresonant. However, electron collisions introduce additional dissipation which modifies Eq. (5). As noted earlier, electrons execute an oscillatory ExB and polarization drift motion due to the wave field (Fig. 1b). The polarization drift is roughly given by $\delta V_p \sim (\omega/\nu_e)\ \delta V_E$ which for the waves in question implies $\delta V_p \ll \delta V_E$. Thus, the dominant electron motion is the ExB drift. Because of collisions, a force is exerted on the electrons; approximately given by $\delta F_e \sim -m_e \nu_e \delta V_E$ where ν_e contains e-e, e-i and e-n collisions. The rate of energy absorption by the electrons is roughly $\dot{W}_{pe} \sim -\delta \underset{\sim}{F}_e \cdot \underset{\sim}{v} \sim \nu_e\, \delta E^2$. The total change in particle energy is

$$\dot{W}_p \sim \left[-\left(v_y \frac{\partial F_{io}}{\partial v_y} \right)_{v_y = \frac{\omega}{k}} + \nu_e \right] \delta E^2 \tag{9}$$

We obtain from Eq. (3) and (4)

$$\gamma \propto \left[\left(v_y \frac{\partial F_{io}}{\partial v_y}\right)_{v_y = \frac{\omega}{k}} - \nu_e\right] \tag{10}$$

Thus, resonant ions give energy to the wave while electrons absorb energy from the wave because of collisions. Instability occurs when $\gamma > 0$ which requires (approximately)

$$\frac{V_{di}}{v_i} > \left(\frac{\nu_e}{k v_i}\right)^{1/2} \tag{11}$$

or

$$L_n < r_{Li} \left(\frac{k v_i}{\nu_e}\right)^{1/2} \tag{12}$$

III. DISCUSSION

Our purpose has been to give a physical discussion of the lower-hybrid-drift instability. This instability is presently the most promising explanation of small-scale irregularities ($\lesssim 1$ m) observed during equatorial spread F. The key features of the mode are:

1. The instability excites a drift wave propagating <u>across</u> the magnetic field.
2. The wave is driven by the free energy provided by the density gradient and the energy exchange occurs via an ion-wave resonance.
3. For an ion-wave resonance to occur the ions must be able to move across the magnetic field. This is possible under two conditions:
   a. In a collisionless plasma, one considers time scales such that $\gamma > \Omega_i$.
   b. In a collisional plasma, ion-ion collisions allow the ions to move across the magnetic field. The condition is $(\nu_{ii}/\Omega_i)k^2 r_{Li}^2 \gtrsim 1$.
4. Electron collisions allow the electrons to absorb energy from the wave and therefore provide a damping mechanism.
5. An approximate threshold condition for instability is:
   a. Collisionless plasma
   $$L_n < r_{Li} (m_i/m_e)^{1/4}$$
   b. Collisional plasma
   $$L_n < r_{Li} (kv_i/\nu_e)^{1/2}$$

Finally, we mention that inclusion of finite electron temperature effects introduces (i) finite electron Larmor radius effects which modify the dispersion properties of the mode and (ii) an electron diamagnetic drift which increases the free energy of the initial equilibrium.

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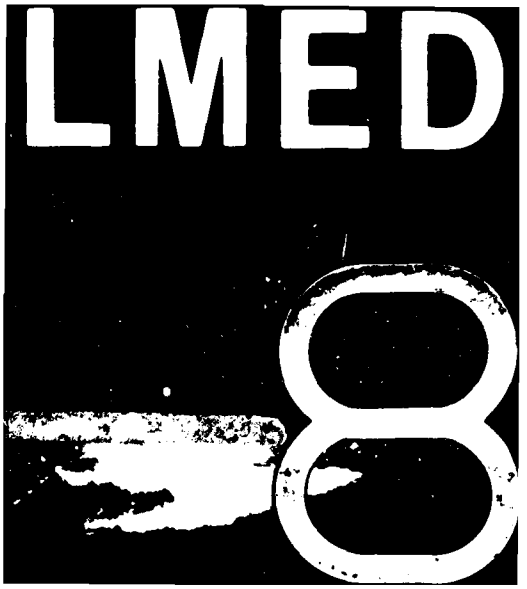
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