Origin of Low-Frequency Oscillations in the Ionosphere

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The threshold current for the ion-acoustic branch is shown to be significantly lower than the ion-cyclotron branch and insensitive to the ion/electron temperature ratio if there is a transverse gradient in the relative magnetic field aligned drift, V_d, and $|(k_y/k_z)(1/\Omega_i)(dV_d/dx)|$ is sufficiently large. The effect persists even when $|dV_d/dx| \rightarrow 0$ provided $(k_z/k_y) \rightarrow 0$, where k_z and k_y are wave vectors along and across the magnetic field and Ω_i is the ion gyrofrequency. Therefore, the ion-acoustic branch is more central to the plasma processes in the ionosphere than is currently believed. [S0031-9007(97)05043-6]

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A fundamental reality throughout the space plasmas is the existence of magnetic field-aligned flows and currents. It is well known that a field-aligned current can support a host of plasma fluctuations and that these fluctuations can, in turn, affect the plasma steady state. The work of Kindel and Kennel [1], which considered the effects of a field-aligned current on ionospheric plasmas, has influenced and guided the interpretation and analysis of *in situ* observations for over two and a half decades. Kindel and Kennel show that, in an infinite homogeneous plasma, the threshold current necessary for the current-driven electrostatic ion-cyclotron (CDEIC) instability [2] is the lowest for ionospheric conditions and, therefore, it is the most likely source for the observed plasma waves which correlate with a field-aligned current.

Although there are some *in situ* ionospheric observations that support the classical CDEIC instability [3,4], a large number of them are at odds with it [5,6]. In particular, the observed signatures are often in the sub-cyclotron frequency range and resemble more closely the ion-acoustic branch [7–9]. A problem of identifying these as the ion-acoustic mode is that they occur for ion/electron temperature ratios of order unity or larger where the classical ion-acoustic modes are severely ion Landau damped [1,10], and, in addition, they are frequently observed for subthreshold currents. We have earlier shown that the inclusion of a localized transverse dc electric field can introduce substantial modifications to the ion-cyclotron wave properties and these modifications can better account for the observed signatures provided that the spatial gradient in the dc electric field is sufficiently strong [11]. In this Letter, we report that, even in the absence of a transverse dc electric field, an infinitesimal transverse gradient in the field-aligned flow can alter the plasma dispersion characteristics sufficiently and make the ion-acoustic branch dominant even when the ion temperature is greater than the electron temperature. This is in sharp contradiction to the behavior in a homogeneous plasma [1].

The effect of a shear in the parallel ion drift was first addressed by D'Angelo [12], who showed the existence of a nonresonant instability whose real frequency is zero in the ion frame but whose growth rate depends on the spatial gradient in the parallel ion flow. Because of the fluid treatment used, the effects of the spatial gradient on wave-particle interactions, which can introduce significant alterations in the ion-acoustic branch, were not realized. To understand such effects, we consider the general kinetic dispersion relation developed by Ganguli *et al.* [13], which assumes a uniform magnetic field in the z direction, a nonuniform dc electric field in the x direction, and a nonuniform magnetic field-aligned plasma flow in the z direction. Assuming no equilibrium electric field and a uniform plasma, but with an inhomogeneous flow parallel to the magnetic field, $V_{d\alpha}(x)$, where α denotes the species, the general dispersion relation in the local limit is given by

$$1 + \sum_n \Gamma_n(b) F_{ni} + \tau(1 + F_{0e}) + k^2\lambda_{Di}^2 = 0\,, \quad (1)$$

where $\Gamma_n(b) \equiv I_n(b)\exp(-b)$, I_n are modified Bessel functions, $b \equiv (k_y\rho_i)^2$, $\tau \equiv T_i/T_e$, $k^2 = k_z^2 + k_y^2$, λ_{Di} is an ion Debye length, and

$$F_{ni} = \left(\frac{\omega}{\sqrt{2}|k_z|v_{ti}}\right)Z\left(\frac{\omega - n\Omega_i}{\sqrt{2}|k_z|v_{ti}}\right) - \frac{V_d'}{u\Omega_i}\left[1 + \left(\frac{\omega - n\Omega_i}{\sqrt{2}|k_z|v_{ti}}\right)Z\left(\frac{\omega - n\Omega_i}{\sqrt{2}|k_z|v_{ti}}\right)\right],$$

$$F_{0e} = \left(\frac{\omega - k_zV_{de}}{\sqrt{2}|k_z|v_{te}}\right)Z\left(\frac{\omega - k_zV_{de}}{\sqrt{2}|k_z|v_{te}}\right) + \frac{V_d'}{\mu u\Omega_i}\left[1 + \left(\frac{\omega - k_zV_{de}}{\sqrt{2}|k_z|v_{te}}\right)Z\left(\frac{\omega - k_zV_{de}}{\sqrt{2}|k_z|v_{te}}\right)\right],$$

where Z is the plasma dispersion function, $u \equiv |k_z|/k_y$, $v_{t\alpha}$ is the thermal velocity, $V_{d\alpha}' \equiv dV_{d\alpha}/dx$, and $\mu \equiv m_i/m_e$. We have assumed $V'_{di} = V'_{de} \equiv V'_d$ and transformed to the ion frame.

The parallel velocity shear can influence the stability of the normal modes in two different ways. First, the existence of shear related terms allows a nonresonant growth. The unstable nonresonant modes are dependent on V'_d and do not require an additional free energy source. From the real part of Eq. (1), we obtain (by expanding the ion Z functions for large argument but electron Z function for small argument, and by using $b \ll 1$, $b/\tau \ll 1$, $k\lambda_{Di} \ll 1$, and with only $n = 0$)

$$\omega = k_z c_s \frac{\sqrt{1 - V'_d/u\Omega_i}}{\sqrt{1 + V'_d/\mu u\Omega_i}} \approx k_z c_s \sqrt{1 - \frac{V'_d}{u\Omega_i}}, \quad (2)$$

since $\mu \gg 1$ and $c_s \equiv (T_e/M_i)^{1/2}$. It follows from Eq. (2) that, for $(1 - V'_d/u\Omega_i) < 0$, there is a purely growing nonresonant mode with $\mathrm{Re}(\omega) = 0$. This is the D'Angelo mode in its simplest form [12]. Since $\mathrm{Re}(\omega) = 0$ (as opposed to $k_z c_s$), it is not the ion-acoustic mode. If the imaginary part of the dispersion relation is included, the essential features of this result will not change although quantitative corrections could be large depending on the parameters [14].

Second, the shear can change the Landau resonance condition for the resonant modes. Let's consider the case with $(1 - V'_d/u\Omega_i) > 0$. Now, Eq. (2) yields a real frequency which is primarily ion acoustic but modified by shear. From Eq. (1), we obtain the growth rate for $\tau \ll 1$, $b \ll 1$, and $k\lambda_{Di} \ll 1$:

$$\gamma \approx \sqrt{\frac{\pi}{8}} \frac{\omega_r}{\sigma^2} \left(\frac{\omega_r}{|k_z| v_{ti}} \right)^3 \times \left[\frac{\tau^{3/2}}{\mu^{1/2}} \left(\frac{k_z V_{de}}{\omega_r} - 1 \right) - \exp\left(- \frac{\omega_r^2}{2(|k_z| v_{ti})^2} \right) \sigma^2 \right], \quad (3)$$

where $\sigma \equiv \sqrt{1 - V'_d/u\Omega_i}$. For $\sigma \to 1$, the expression for the classical current-driven electrostatic ion-acoustic (CDEIA) mode [15] is recovered.

The condition $\gamma = 0$, with ω_r given by Eq. (2), leads to the critical electron drift V^c_{de}:

$$\frac{V^c_{de}}{v_{ti}} = \frac{\sigma}{\tau^{1/2}} + \frac{\mu^{1/2}\sigma^3}{\tau^2} \exp\left(- \frac{\sigma^2}{2\tau} \right). \quad (4)$$

Again, for $\sigma = 1$, we recover the critical drift behavior for the homogeneous CDEIA mode; i.e., V^c_{de} rapidly increases with τ because of the sensitive τ dependence of the exponent term, describing the ion Landau damping [1,15].

For the general case, one can minimize V^c_{de} with respect to σ to obtain σ_m such that

$$1 + \frac{\mu^{1/2}\sigma_m^2}{\tau^{3/2}} \exp\left(- \frac{\sigma_m^2}{2\tau} \right) \left(3 - \frac{\sigma_m^2}{\tau} \right) = 0. \quad (5)$$

Solving Eq. (5) for σ_m and substituting into Eq. (4) yields the minimum critical drift in the presence of shear, which is found to be significantly less than that for the homogeneous case. This is because $\sigma_m > 1$ and σ_m increases with τ. Physically, this implies that the phase velocity ω_r/k_z increases in comparison with the homogeneous case and this difference grows with τ. This is a major departure from the homogeneous case, where stabilization of the mode with increasing τ occurs due to the shift of the phase velocity into the region of strong ion Landau damping. Shear enables the mode to shift out of the damping region by increasing the parallel phase speed by a factor of σ.

Numerical analysis of Eq. (1) shows that, in the presence of shear, Eqs. (3) and (4) remain to be good approximations for a wide range of τ. This is unlike the homogeneous case, where these approximations are reasonable only for $\tau \ll 1$.

It is found that, in a wide range of τ, σ_m is larger than unity and V^c_{de} is significantly below the critical drift for both the homogeneous CDEIA and CDEIC instabilities. In contrast to the homogeneous case, the value of (V^c_{de}/v_{ti}) in the presence of shear is almost insensitive to τ variations and $(V^c_{de}/v_{ti}) \approx 5$ for a wide range of τ (from 0.1 to 10). These conclusions are supported by numerical solutions of the dispersion relation [Eq. (1)] without any simplifying approximations and are shown in Fig. 1. Here, we compare the τ dependence of the critical drift for the homogeneous CDEIA and CDEIC modes, and the CDEIA mode in the presence of shear for $|V'_d/\Omega_i| = 0.1$. For such shear values, the modification to the CDEIC mode is negligible.

It is remarkable that V^c_{de} for the CDEIA mode does not depend on the shear strength as long as $V'_d \neq 0$. Even when $V'_d \to 0$, the critical drift remains unchanged if $u \to 0$ so that $V'_d/u\Omega_i$ remains constant. A discontinuous jump to the critical value for the homogeneous CDEIA mode occurs at $V'_d = 0$. Thus, an infinitesimal shear can

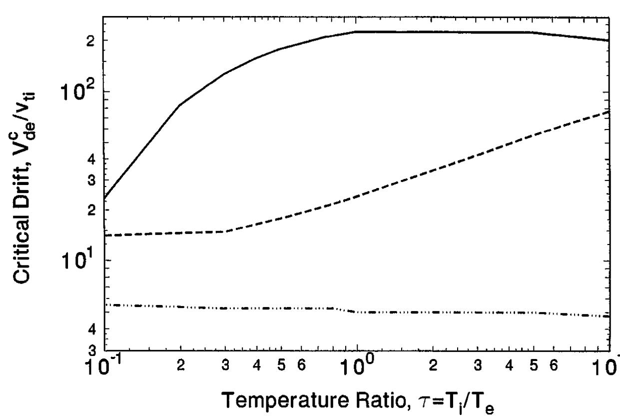

FIG. 1. Temperature ratio dependence of the critical electron drift obtained from Eq. (1) for the homogeneous CDEIA and CDEIC modes (solid and dashed lines, respectively), and for the ion-acoustic mode in the presence of shear $|V'_d/\Omega_i| = 0.1$ (dash-dotted line). Critical drift is minimized with respect to parallel and transverse wave numbers. Here, $\mu = 29\,392$ (O^+ plasma) and $\Omega_e/\omega_{pe} = 10$.

drastically reduce the critical drift, while its magnitude determines the obliqueness of the marginally stable mode. The obliqueness of the marginally stable mode can be expressed as

$$|u| = \frac{|V_d'|}{\Omega_i} \frac{1}{\sigma_m^2 - 1}. \tag{6}$$

This relation is affirmed by the numerical solution of the more rigorous Eq. (1) for sufficiently small shear. Since σ_m increases with τ, for a given V_d', u must decrease. This makes the ion-acoustic mode more flutelike with increasing τ.

Unlike the ion-acoustic branch, the critical drift for the ion-cyclotron branch depends continuously on V_d'. Therefore, for small enough V_d', there is no noticeable difference in homogeneous CDEIC mode properties. For the parameters used in Fig. 1, results for homogeneous and inhomogeneous CDEIC modes are almost indistinguishable. Detailed analysis of the ion-cyclotron branch in the presence of parallel flow shear will be presented elsewhere.

There are obvious differences between the mode discussed here and the D'Angelo mode, although a velocity shear in the parallel ion flow plays the central role in either case. For example, the D'Angelo mode has $\mathrm{Re}(\omega) = 0$, while, for this mode, $\mathrm{Re}(\omega) \approx k_z c_s \sqrt{1 + |V_d'/u\Omega_i|} > 0$. This implies a narrow frequency spectrum around the zero frequency for the D'Angelo mode, while a broader spectrum for the ion-acoustic mode. While the D'Angelo instability requires $V_d'/u\Omega_i > 1$, the resonant ion-acoustic instability requires $V_d'/u\Omega_i < 0$. The D'Angelo instability is a fluid mode due to velocity gradient and almost insensitive to the field-aligned drift, while the ion-acoustic mode we discuss is kinetic in nature and is essentially current driven $(\omega_r/k_z < V_{de})$ while shear plays the role of a catalyst. Consequently, this mode has a much broader range of wave characteristics (obliqueness, etc.) than the D'Angelo mode. Also, the D'Angelo mode is stabilized by a transverse density gradient [12], while it can be shown that the opposite is true for the ion-acoustic mode.

The difference between the classical homogeneous CDEIA mode and the shear modified ion-acoustic mode considered here is not just in the reduction of the critical drift and enlargement of the τ range. While for the classical CDEIA mode, $(k_z \lambda_{De}) \sim 1$ and $\omega_r \sim \omega_{pi}$ corresponding to the most unstable mode for supercritical drifts [1], the situation in the presence of shear is different. It is found that the maximum growth occurs for $(k_z \lambda_{De}) \ll 1$ and $\omega_r \ll \omega_{pi}$. It is interesting to note that the wavelength and frequency range of the ion-acoustic oscillations observed in the laboratory experiments is usually $(k_z \lambda_{De}) \ll 1$ and $\omega_r \ll \omega_{pi}$ [16]. This suggests that shear, which is unavoidable in experiments, may significantly influence the outcome. The role of dV_d/dx in fusion plasmas has also been extensively discussed [17].

The implication of these results to the analysis of *in situ* space data is significant. Observations of low-frequency ion-acoustic-like waves in the ionosphere, where $\tau \sim 1$ [7,8] and $\tau \gg 1$ [9], cannot be adequately explained using the homogeneous plasma approximation [18], especially since the magnitude of the field-aligned currents is often found to be small. Since the existence of a V_d' is more normal than the exception in space plasmas [19], the origin of low-frequency waves becomes clear when this inhomogeneity is accounted for. There are other advantages as well. Since it is easy to excite and sustain the ion-acoustic modes in realistic ionospheric conditions, the formation of electrostatic solitary structures due to nonlinear evolution of ion-acoustic modes [20] becomes a more plausible scenario. Also, it has been demonstrated that wave-particle interactions and anomalous transport is necessary to explain a number of features observed in the ionosphere [21], such as the formation of density cavities and their correlation with plasma waves [6], the formation of temperature anisotropy with $T_\perp > T_\parallel$ [22], large electron temperatures, etc. Since the threshold for the shear modified ion-acoustic instability is very low, the anomalous resistivity and transport resulting from this instability is likely to play a crucial role in defining the ionosphere-magnetosphere coupling and, hence, the ambient plasma state in the near Earth region. More generally, the results discussed here, in conjunction with our earlier works [11,13] and more recent observations [7–9,23], emphasize the vital role of the inhomogeneities in the ionosphere which, contrary to the general notion, is far from a largely laminar state.

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