Nonlinear Studies of Farley-Buneman waves

Linear theory gives conditions for the onset of an instability and characteristics of the initial growing waves but cannot explain saturation or provide the amplitude and spectral characteristics of developed turbulence. A number of theoretical models have been developed to explain saturated FB waves. Hamza and St.-Maurice [1993a, b] proposed a strongly turbulent mode-coupling theory based upon a two-fluid model. Another approach, developed by Albert and Sudan [1991], Sahr and Farley [1995], Otani and Oppenheim [1998] and Dimant [2000], uses a truncated three-wave mode-coupling dynamic model to explain instability saturation. None of these theories provides a fully consistent quantitative description of nonlinear saturation of E-region instabilities.

Simulation Studies of Farley-Buneman Waves

Two-dimensional simulations of equatorial Farley-Buneman waves have enabled researchers to understand a number of key electrojet observations. They show that the dominant nonlinearity arises when the perturbed electric fields interact with the density perturbations and drive energy into modes which are linearly stable or damped. This wave-wave interaction modifies the linear behavior of the waves in a number of observable ways. It leads to mode coupling which saturates the waves when \(|\langle \delta E \rangle | \sim E_0\) where \(|\langle \delta E \rangle|\) is the average amplitude of the perturbed electric field generated by the waves. This causes a broadening of the turbulent spectrum and also reduces the expected dominant phase velocity below that predicted by linear theory [Oppenheim and Otani, 1996]. This results from mode coupling when the perturbed fields of secondary modes, on average, reduce or cancel the driving field, \(E_0\), of the primary modes [Otani and Oppenheim, 1998]. However, this model and the 2D simulations do not predict a strict sound-speed saturation.

The simulations also show that FB waves nonlinearly drive a large-scale (D.C.) current in the E-region ionosphere as shown in figure 1 [Oppenheim, 1997]. This current flows parallel to the fundamental Pedersen current and with a comparable magnitude. These currents can restructure the electrojet as shown in figure 2. Also, by effectively increasing the pedersen currents, wave-driven currents reduce the electrojet charge and polarization field, \(E_{0}\), responsible for driving FB waves. This makes the linear phase velocity drop toward the acoustic speed and may play an important role in sound speed saturation of type 1 waves.

A wave-driven current results from two fundamental features of E-region plasma waves. First, electrons travel mostly perpendicular to the electric fields due to the geo-
magnetic field while ions travel mostly parallel to the fields because ion-neutral collisions make magnetic field effects inconsequential. Second, gradient-drift and two-stream instabilities cause compressional waves where the plasma density enhancements and the perturbed electric fields remain largely in phase. At the plasma density maxima of the propagating wave fronts, electrons move perpendicular to the wave direction and the geomagnetic field. At the density minima, electrons move in the opposite direction with an equal velocity. However, more electrons exist at the maxima than at the minima causing a greater current in one direction than the other, resulting in a net (direct) current.

The electric fields measured by rockets passing through gradient-drift waves often appear as irregular square waves [Pfaff Jr. et al., 1987]. Wave-driven electron currents can cause these squared-off electric fields through a two-step process. First, the perturbed electric field of a gradient-drift wave must exceed the threshold necessary to initiate two-stream waves [Sudan et al., 1973]. Second, these secondary two-stream waves generate wave-driven electron currents which modify the original gradient-drift waves. This effect has been estimated numerically in [Oppenheim, 1997] and shown in figure 3.

**Thermal effects**

In the mid-1990s [Dimant and Sudan, 1995, 1997] showed the important effects that temperature perturbations can play in E-region irregularities by predicting the existence of a new type of wave which results from temperature modulations of electrons and extends down into the upper D region, where no other known instabilities exist. This unique feature and good correlation with the electric field strength allowed them to identify the new instability in available rocket data [Blix et al., 1996]. Evidence for the new instability may also exist in the HF radar observations by Tsunoda et al. [1997]. Additionally, some spectral features of the turbulence observed by rockets during the ERRRIS campaign probably also resulted from the ET instability [Pfaff et al., 1992; Pfaff, 1996]. At higher altitudes, the ET instability has similar growth rates as the FB and GD instabilities and likely produces a portion of the observed radar echoes [Robinson, 1998; St.-Maurice and Kissack, 2000].

More recently, Kagan and Kelley [2000] and Dimant and Oppenheim [2004] have developed the theory of an ion thermal (IT) instability mechanism, similar to the electron thermal one discussed above to explain neutral-wind driven radar and rocket measurements in mid-latitude sporadic E-layers. Both the IT and FB instabilities generate waves with similar wavelengths which may contribute to type 1 signals, particularly from high altitudes.

The physics underlying these new instabilities derives from including a heat flow equation for the electrons and/or ions. The classical Farley-Buneman assumes adiabatic electrons and isothermal ions. However this breaks down for the ions at the top of the E-region when the collision rate becomes similar to the wave frequency. Likewise, at low E and upper D region altitudes, the electron collision rates become sufficiently high to allow non-adiabatic behavior to dominate. Even in the middle of the E-region, thermal effects can matter for strongly driven waves as found at high latitudes. To explain heating and cooling of both species, these more recent papers assume that the entropy of the system increases at a rate described by

$$\frac{n^{2/3} \, d}{dt} \left( \frac{T_{i,e}}{n^{2/3}} \right) = \frac{2}{3} \mu_i \nu_{i,e} V_{i,e}^2 - \delta_{i,e} \nu_{i,e} (T_{i,e} - T_n) + Q_{i,e}$$

where $\mu_i$ are the reduced ion and electron masses, $\mu_{i,e} = m_{i,e} n_i / (m_{i,e} + m_n)$; $\delta_{i,e}$ is the average fraction of energy lost by the ion or electron during one collision, $\delta_{i,e} = 2m_{i,e} / (m_{i,e} + m_n)$; $m_n$ is the average mass of the neutral species; $\nu_i$ and $\nu_e$ are the ion-neutral and electron-neutral collision rates; $T_{i,e,n}$ are the ion, electron and neutral temperatures in energy units; $V_{i,e}$ gives the average drift speed of the ion or electron population; and $Q_{i,e}$ includes other terms such as heat conductance and diffusion which become important at short wavelengths [Kissack et al., 1995]. When the R.H.S of this equation is small, as is usually the case for electrons in the upper E-region and short wavelength modes, then this equation predicts adiabatic behavior. When the collisional cooling term dominates over the other terms, as is the case for ions in the lower E-region, then this equation predicts isothermal behavior. Ion thermal effects become important when the collisional heating and collisional cooling respond to the changing velocities and temperatures within a wave as we find occurs within the upper E-region.
or for strongly driven instabilities.

**What drives thermal instabilities?** The physics underlying these thermal instabilities differs from that of the FB or GD instabilities but is no more difficult to understand. When no waves exist, then ion and electron heating arises when they pederson drift in response to the ambient electric field, $\vec{E}_0$, and cool due to collisional cooling. A balance between heating and cooling develops which elevates their temperatures above the neutral gas temperature. When a wave develops the perturbed electric field $\delta \vec{E}$, can add or subtract to $\vec{E}_0$ depending on the orientation of the wave. If they add in regions of reduced density, then the resulting enhanced pressure will work to reduce the density further creating instability as shown in figure 4. This will lead to waves oriented in a direction different from $\vec{E}_0 \times \vec{B}_0$ and have a number of characteristics which differ from FB waves.

Thermal effects modify E-region instability thresholds as shown in Fig. 5. At higher altitudes, the ion thermal (IT) effects reduce the threshold and increase the maximum altitude for instability. At lower altitudes, the electron thermal instability reduces the threshold and the minimum altitude. The IT mechanism also plays an important role for sufficiently strong DC electric field, especially in the nonlinear stage of instability saturation [Oppenheim and Dimant, 2004].

**Oppenheim and Dimant** [2004] used fully kinetic 2-D simulations to show how strongly driven electrojets instabilities are strongly influenced by ion thermal effects. A number of features distinguish these waves from FB waves: (1) The wave vector of the dominant modes tilt away from the strictly $\vec{E} \times \vec{B}$ direction toward $-\vec{E}_0$ (see fig. 6). (2) Ion temperature becomes elevated overall and specifically in
regions of reduced density (see fig. 6. (3) The saturation mechanism for these waves is influenced by both FB type mode-coupling and thermal dissipation.

References


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Figure 6. Panels showing perturbations in the spatial variation of ion density, ion temperature, and electron temperature at the end of the linear growth stage of the instability at 27.6 ms. The temperature of species $s$ is defined by $T_s = m_s |\langle (\vec{v}_s - \langle \vec{v}_s \rangle)^2 \rangle| / k_B$ where the $p$ subscript indicates the species, $i$ for ions and $e$ for electrons, $\hat{x}$ points in the $\vec{E}_0 \times \vec{B}$ direction and $\hat{y}$ points in the $\vec{E}_0$ direction, $m_s$ is the atomic mass for species $s$, $k_B$ is the Boltzmann constant and $\langle a \rangle$ indicates averaging of the quantity $a$ for all particles [Oppenheim and Dimant, 2004].