SESSION V

ANOMALOUS TRANSPORT IN CURRENT SHEETS

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ABSTRACT

A review of several microinstabilities that have been suggested as possible anomalous transport mechanisms in current sheets is presented. The specific application is to a 'field reversed plasma' which is relevant to the so-called 'diffusion region' of a reconnection process. The linear and nonlinear properties of the modes are discussed, and each mode is assessed as to its importance in reconnection processes based upon these properties. It is concluded that the two most relevant instabilities are the ion acoustic instability and the lower-hybrid-drift instability. However, each instability has limitations as far as reconnection is concerned, and more research is needed in this area.

I. INTRODUCTION

The subject of anomalous transport in current sheets is of great interest to space plasma physicists, especially as it can impact collisionless reconnection processes. A simple concept of a reconnection process is illustrated in Fig. 1, which depicts a field-reversed plasma. The magnetic field $\underset{\sim}{B}$ is in opposite directions on the two sides of the neutral line, and a uniform electric field $\underset{\sim}{E}$ is directed into the page. The plasma motion in this configuration is roughly described by Ohm's law, which for the present situation may be written $\underset{\sim}{E} + \underset{\sim}{U} \times \underset{\sim}{B} = \eta \underset{\sim}{J}$ where $\underset{\sim}{U}$ is the plasma velocity, η the resistivity, and $\underset{\sim}{J}$ the current density). Away from the neutral line, the resistivity term is usually small, and the plasma obeys $\underset{\sim}{E} + \underset{\sim}{U} \times \underset{\sim}{B} = 0$, which is sometimes called the frozen-in-field condition. Loosely speaking, this means that particles are tied to a particular magnetic-field line. In this region, far from the neutral line, the plasma and the magnetic field are carried towards the neutral line with a velocity $U_{in} \simeq E/B$. However, the frozen-in-field condition breaks down in the diffusion region, where the magnetic field becomes very weak. The governing equation is $\underset{\sim}{E} = \eta \underset{\sim}{J}$, and the plasma and magnetic field are decoupled, i.e., no longer tied together. When

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this occurs the magnetic field can slip through the plasma and reconnect. The plasma and magnetic field then leave the diffusion region with a velocity U_{out} as shown in Fig. 1. In this process $U_{out} > U_{in}$, so that the plasma energy has been increased at the expense of magnetic-field energy.

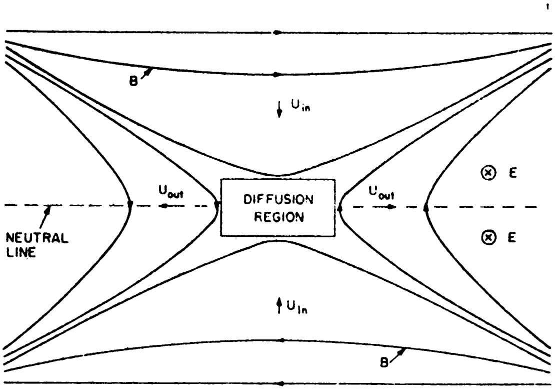

Figure 1: Schematic of a forced reconnection process.

One of the problems in applying this model to collisionless space plasmas (such as the earth's magnetotail) is properly describing the diffusion region. The resistivity η associated with coulomb collisions between particles is very small in space; the plasma is essentially collisionless. What then can balance the electric field in the diffusion region? There are other terms in Ohm's law, such as electron inertia and pressure anisotropy, but these also appear to be quite small (Vasiliunas, 1975). Another explanation is the occurrence of anomalous resistivity in the diffusion region. In this situation, particles scatter off collective electric fields generated by a plasma microinstability, and this scattering process decouples the plasma from the magnetic field. Recent laboratory experiments (Gekelman et al., 1982; Stenzel et al., 1983) in fact report observations of anomalous scattering.

Incorporating microturbulence effects in a reconnection process is a formidable task. Several issues need to be addressed. First, the linear theory of a microinstability needs to be developed appropriate for the plasma and magnetic field configuration of the diffusion region. In this study it is important to determine the relevant plasma conditions needed to excite the instability (e.g., width of the current sheet, electron/ion temperature ratio, etc.). Second, a nonlinear theory of the microinstability in question needs to be developed. Here, it is crucial to determine the level of microturbulence produced by the instability (i.e., saturation energy), and whether or not the turbulence is steady state. Finally, given the linear and nonlinear properties of the unstable waves, this information needs to be self-consistently incorporated into the hydrodynamic flows associated with a reconnection process. Development of such a self-consistent theory of collisionless reconnection is indeed difficult.

In general, plasma theorists have focussed on the first two issues: the linear and nonlinear theories of a microinstability as it applies to the diffusion region. The final issue, incorporating turbulence into reconnection flows, has been ignored. [A notable exception to this is the work of Coroniti and Eviatar (1977).] Although this may be considered, perhaps, a "cop-out" on the part of plasma theorists, the information regarding plasma microturbulence in the diffusion region is still crucial to understanding the overall process. Moreover, the anomalous transport properties of instabilities in the diffusion region can be modelled and incorporated into 2D and 3D MHD simulations of reconnection (Sato and Hayashi, 1980; Ugai, 1983; Sato, these proceedings). Although this is not self-consistent, it does provide insight into the collisionless reconnection process.

In this spirit, the purpose of this paper is to review the various microinstabilities that have been suggested to play a role in reconnection phenomena. Hence, only the linear and nonlinear properties of the instabilities will be discussed. Based upon these properties one can then assess whether or not a particular instability is a viable source of anomalous resistivity for a reconnection process. Finally, it should be noted that a review article of this nature has been published (Papadopoulos, 1979). The present work, in fact, draws heavily from Papadopoulos (1979); however, we attempt to elucidate certain aspects of the problem not emphasized in Papadopoulos (1979), and to present new results that have been obtained in the past four years.

The organization of the paper is as follows. In the next section, we describe the basic plasma and magnetic field configuration under consideration. In Section III, a description of the linear and nonlinear properties of several macroinstabilities is given. In Section IV, a discussion of the relevance of each of these instabilities to a reconnection process is presented. Finally, the last section contains a summary of the important results obtained to date.

II. PLASMA AND FIELD CONFIGURATION

The basic plasma and magnetic field configuration to be considered in this review is shown in Fig. 2. We take a simple, 1D reversed field geometry shown in Fig. 2a. The magnetic field $\underset{\sim}{B}$ reverses direction at x = 0 and is supported by a plasma current $\underset{\sim}{J}$ which is peaked at x = 0. The width of the reversal layer (or current sheet) is given by λ. An important parameter shown in Fig. 2a is x_e and x_i where $x_\alpha = (2\rho_\alpha\lambda)^{1/2}$, where ρ_α is the mean Larmor radius of the α species, and typically $x_e << \lambda < x_i$. This parameter will be discussed shortly. In Fig. 2b, the slab geometry used in the stability analysis is shown. The magnetic field $\underset{\sim}{B}$ is in the + or - z direction, the density gradient ∇n is directed towards x = 0, the magnetic field gradient ∇B is directed away from x = 0, and the current $\underset{\sim}{J}$ is in the y direction. For the purposes of this review, the microinstabilities discussed are driven <u>solely by the cross-field current J.</u> Thus, the wave vector $\underset{\sim}{k}$ for the instabilities discussed is in the same direction as $\underset{\sim}{J}$, i.e., $\underset{\sim}{k} = k\, e_y$. Instabilities driven by particle distribution functions which include beams, tails, or temperature anisotropies are not considered.

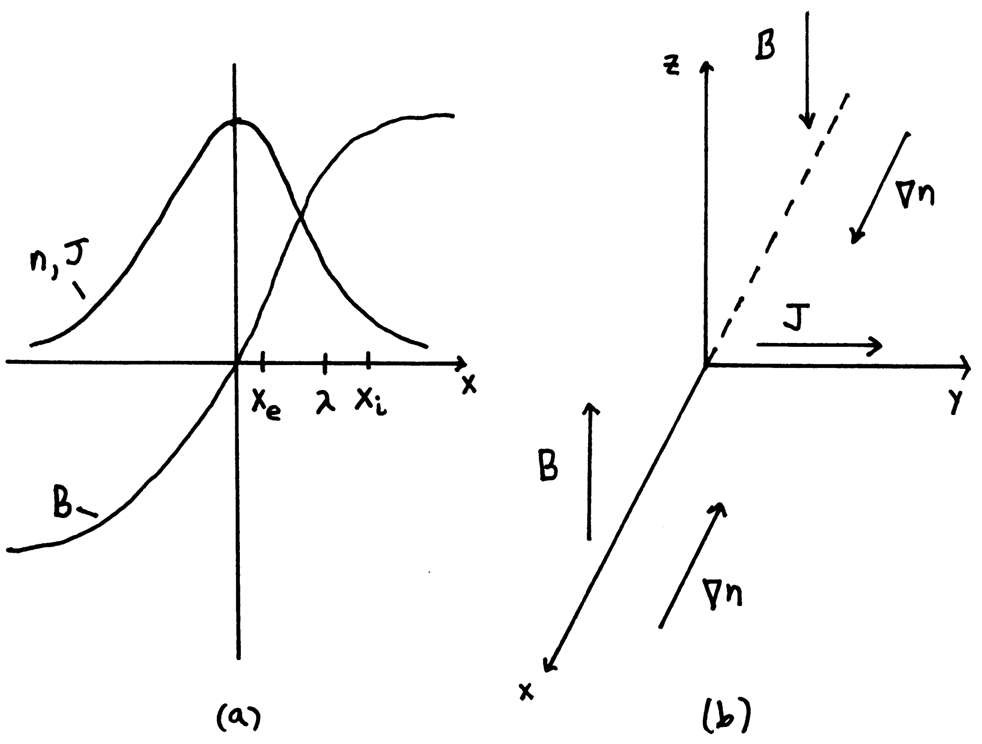

Figure 2: Plasma configuration and geometry.

Finally, we make one further simplifying assumption in the analysis which concerns the parameter $x_\alpha = (2\rho_\alpha\lambda)^{1/2}$ (Hoh, 1966). This quantity indicates the boundary of crossing and non-crossing thermal particles. Thermal particles in the region $|x| < x_\alpha$ cross the "neutral line", i.e., pass through the magnetic null region $B = 0$ at $x = 0$. These particles execute rather complicated orbits not amenable to analysis. On the other hand, thermal particles in the region $|x| > x_a$ do not cross the "neutral line". These particles are magnetized and execute gyro-orbits about $\underset{\sim}{B}$. Thus, we consider two regimes: unmagnetized electrons ($|x| < x_e$) and magnetized electrons ($|x| > x_e$). The ions are taken to be unmagnetized which is valid for $|x| < x_i$ or $\gamma > \Omega_i$ where γ is the growth rate of an instability and $\Omega_i = eB/m_ic$ is the ion gyrofrequency. The assumption of unmagnetized electrons (i.e., "straight line orbits") is an over-simplification but is reasonably valid for $|x| \ll x_e$.

III. REVIEW OF MICROINSTABILITIES

A. Unmagnetized Regime ($|x| < x_e$)

1. Buneman instability

The Buneman instability is the classic electron-ion two-stream instability (Buneman, 1959). It is a fluid-like (or hydrodynamic) instability in that it does not involve wave-particle resonances (i.e., $\omega/k \gg v_\alpha$ where $v_\alpha = (T_\alpha/m_\alpha)^{1/2}$ is the thermal velocity of species α). The turn-on condition for instability is roughly $V_d \gtrsim 2v_e$ where V_d is the relative electron-ion drift. In the linear regime at maximum growth one finds that $\omega_r \simeq \omega_{pe}$, $\gamma \simeq (m_e/m_i)^{1/3}\omega_{pe}$ and $k \simeq V_d/\omega_{pe} \lesssim \lambda_{de}^{-1}$ where $\omega = \omega_r + i\gamma$, $\omega_{pe} = (4\pi n_e^2/m_e)^{1/2}$ is the electron plasma frequency, and $\lambda_{de} = v_e/\omega_{pe}$ is the electron Debye length (Krall and Trivelpiece, 1973). Thus, the instability is considered to be high frequency and short wavelength. In the nonlinear regime the instability is saturated by electron trapping which leads to strong electron heating (i.e., $v_e \gtrsim V_d$) (Davidson et al., 1970; Biskamp and Chodura, 1973). In the presence of a steady state electric field, the anomalous resistivity η_{an} is not steady state (i.e., $\eta_{an} \sim$ constant) but is spiky (Papadopoulos, 1977).

2. Ion acoustic instability

The ion-acoustic instability, like the Buneman instability, is driven by the relative electron-ion drift V_d. However, the ion acoustic instability is a resonant (or kinetic) instability and is driven via an electron-wave resonance. The turn-on condition for this instability is somewhat less stringent than that of the Buneman instability when $T_e \gg T_i$. The condition is approximately $V_d \gtrsim (T_i/$

$m_e)^{1/2}$ for $0.2 < T_e/T_i < 5.0$ (Coroniti and Eviatar, 1977). However, when $T_e \lesssim T_i$ the turn-on is comparable to that of the Buneman instability. Linear theory predicts (at maximum growth) that $\omega_r \simeq kc_s \simeq \omega_{pi}$, $\gamma \simeq (m_e/m_i)^{1/2}(V_d/c_s)\omega_{pe}$ and $k \sim \lambda_d^{-1}$ where $c_s = (T_e/m_i)^{1/2}$ is the ion sound speed and $\omega_{pi} = (4\pi\ ne^2/m_i)^{1/2}$ is the ion plasma frequency (Papadopoulos, 1979).

There have been many nonlinear theories of the ion-acoustic instability proposed (e.g., quasilinear, resonance broadening, nonlinear Landau damping). Rather than discuss any of these theories in detail it will simply be noted that (1) a steady state anomalous resistivity can be achieved (Coroniti and Eviatar, 1977), and (2) near marginal stability, the anomalous collision frequency is roughly $\nu_{an} \simeq 10^{-2}\omega_{pe}$ (Papadopoulos, 1979) so that the anomalous resistivity is $\eta_{an} = 4\pi\nu_{an}/\omega_{pe}^2 \simeq 10^{-1}\omega_{pe}^{-1}$.

B. Magnetized instabilities ($|x| > x_e$)

1. Beam cyclotron instability

The beam cyclotron instability (also known as the electron cyclotron drift instability) (Wong, 1970; Lampe et al., 1972) is a fluid-like (or hydrodynamic) instability that is excited via the coupling of an electron Bernstein wave to an ion mode. The relative electron-ion drift allows the ion mode to be Doppler-shifted so that its frequency matches an electron cyclotron harmonic. The turn-on condition for this instablity is $V_d >$ Max $[c_s, (\Omega_e/\omega_{pe})v_e]$ where $c_s = (T_e/m_i)^{1/2}$ (Papadopoulos, 1979). For the case $T_e << T_i$, maximum growth is characterized by $\omega_r \simeq k(c_s + V_d)$, $\gamma \simeq (m_e/m_i)^{1/4}\Omega_e$ and $k \simeq \lambda_{de}^{-1}$ (Lampe et al., 1972). The mode saturates because of turbulent scattering of the electrons which effectively "demagnetize" them and they are unable to maintain coherent gyro-orbits (Lampe et al., 1971). The saturation energy of the instability is relatively small so that a small anomalous collision frequency results: $\nu_{an} \simeq (V_d/v_e)^3\Omega_e$ (Papadopoulos, 1979).

2. Magnetized ion-ion instability

The magnetized ion-ion instability (Papadopoulos et al., 1971) is a counter-streaming ion-ion instability. It is a fluid-like (or hydrodynamic) instability. The turn-on condition for this instability is $V_{ii} \gtrsim 2v_i$ where V_{ii} is the relative ion-ion drift. At maximum growth one can show that $\omega_r \simeq 0$, $\gamma = \omega_{\ell h}$ and $k \simeq \omega_{\ell h}/V_{ii}$ where $\omega_{\ell h} \simeq \omega_{pi}/(1 + \omega_{pe}^2/\Omega_e^2)^{1/2}$ is the lower-hybrid frequency. However, the instability is linearly stable when $V_{ii} > V_A(1 + \beta_e)^{1/2}$ where $V_A = B/(4\pi nm_i)^{1/2}$ is the Alfvén velocity and $\beta_e = 8\pi nT_e/B^2$. The mode saturates because of ion trapping and produces strong ion heating as well as a reduction in the relative ion-ion drift velocity. The anomalous ion-ion collision frequency associated with this instability is $\nu_{an} \lesssim 10^{-1}\omega_{\ell h}$ (Lampe et al., 1975).

3. Lower-hybrid-drift instability

The lower-hybrid-drift instability (Davidson et al., 1977) is a resonant (or kinetic) instability which is excited via an ion-drift wave resonance when $V_{di} \lesssim v_i$ (here, $V_{di} = (v_i^2/\Omega_i)\partial \ell n\, n/\partial x$ is the ion diagmagnetic velocity). The turn-on condition for the instability is $V_{di} > v_i(m_e/m_i)^{1/4}$. The instability is characterized at maximum growth by $\omega_r \simeq kV_{di} \lesssim \omega_{\ell h}$, $\gamma \simeq (V_{di}/v_i)\omega_r$ and $k\rho_e \sim (T_e/T_i)^{1/2}$ where ρ_e is the mean electron Larmor radius. This instability is relatively insensitive to the temperature ratio T_e/T_i. However, the mode is suppressed in high β plasmas because of an electron ∇B drift-wave resonance. A variety of nonlinear theories have been suggested for the lower-hybrid-drift instabilities (e.g., quasilinear relaxation, resonance broadening, ion trapping, mode coupling). Again, we will not discuss these in detail but note that the most likely saturation mechanism is mode coupling (Drake et al., 1983). The anomalous collision frequency associated with the turbulence is $\nu_{an} \simeq (V_{di}/v_i)^2\omega_{\ell h}$ and a steady state resistivity can result from this turbulence.

IV. APPLICATION TO RECONNECTION

Prior to discussing the relevance of each instability discussed in Section III to reconnection, it is important to note a major difference between the magnetized and unmagnetized instabilities. Namely, the spatial region where these instabilities can exist. As noted in Section II the unmagnetized instabilities are limited to $|x| < x_e$, i.e., essentially the null region where $\underset{\sim}{B} \simeq 0$. This is precisely where one would like microturbulence to exist in order to "decouple" the plasma from the magnetic field. On the other hand, the magnetized instabilities are restricted to $|x| > x_e$, away from the null field region. Thus, these instabilities do not <u>directly</u> produce an anomalous resistivity in the null region. However, the dynamic evolution of the plasma and field in a reconnection process may allow penetration of the magnetized modes to the region $|x| < x_e$ (e.g., current steepening, convection).

A. Unmagnetized instabilities

1. Buneman instability

The Buneman instability requires a strong relative electron-ion drift to be excited (i.e., $V_d \gtrsim 2v_e$). By using Ampere's law to relate the width of the current sheet (λ) to the relative drift (V_d), one can show that $\lambda < c/\omega_{pe}$ for this instability to be excited in the diffusion region. Because of the extremely thin current sheet needed, it seems unlikely that the Buneman instability can be of any importance to collisionless reconnection processes.

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2. Ion acoustic instability

A theory of reconnection incorporating the ion acoustic instability as a source of anomalous resistivity has been developed by Coroniti and Eviatar (1977). For a detailed discussion, we refer the interested reader to this paper. However, several comments on this work are in order. First, the model developed by Coroniti and Eviatar (1977) is reasonably self-consistent although a number of simplifying assumptions were required for the analysis. Second, they found that steady state reconnection could occur based upon ion acoustic wave turbulence for certain parameter regimes. Third, even though the turn-on condition for the ion acoustic instability is less stringent than that for the Buneman instability, a thin current sheet is still required to excite this mode, i.e., $\lambda \lesssim$ few (c/ω_{pe}), especially for plasmas such that $T_e << T_i$. Finally, although ion acoustic turbulence has been observed in laboratory reconnection experiments (Bratenahl and Yeates, 1970) its exact role is unclear. Moreover, in space plasmas, it is unlikely that current sheets develop as thin as required for this instability (e.g., the earth's magnetotail). Thus, the ion acoustic instability is probably not important for reconnection processes in collisionless space plasmas.

B. Magnetized plasmas

1. Beam cyclotron instability

The beam cyclotron instability has been discussed in regard to reconnection by Coroniti and Eviatar (1977) and by Haerendel (1978). As noted by Papadopoulos (1979), thin current sheets ($\lambda \lesssim$ few (c/ω_{pe})) are needed to produce a significant anomalous resistivity. Also, it has been shown that a magnetic field gradient (∇B) substantially reduces the growth rate of this instability (Gary, 1972; Sanderson and Priest, 1972). Thus, we conclude that the beam cyclotron instability is not important to reconnection processes.

2. Magnetized ion-ion instability

The magnetized ion-ion instability has recently been proposed as a source of anomalous resistivity for magnetotail reconnection by Lee (1982). However, the plasma configuration required is somewhat more complicated than shown in Fig. 2a. That is, a second electron and ion species is also considered as shown in Fig. 3. This second plasma is labelled untrapped. At the position $x = x_0$ in Fig. 3, the diagmagnetic drifts of the two ion species are in opposite directions so that ion counter-streaming occurs. Based on this type of plasma configuration, Lee (1982) finds that he magnetized ion-ion instability can be unstable. It should be noted that (1) the scale lengths of the density gradients need to be relatively sharp ($L_n < \rho_i$ where $L_n \simeq (\partial \ln n/\partial x)^{-1}$) in order that the instability turn-on $V_{ii} > 2v_i$; (2) the mode is stable in high β plasmas; and (3) the important effect of electron ∇B damping has been ignored in Lee (1982).

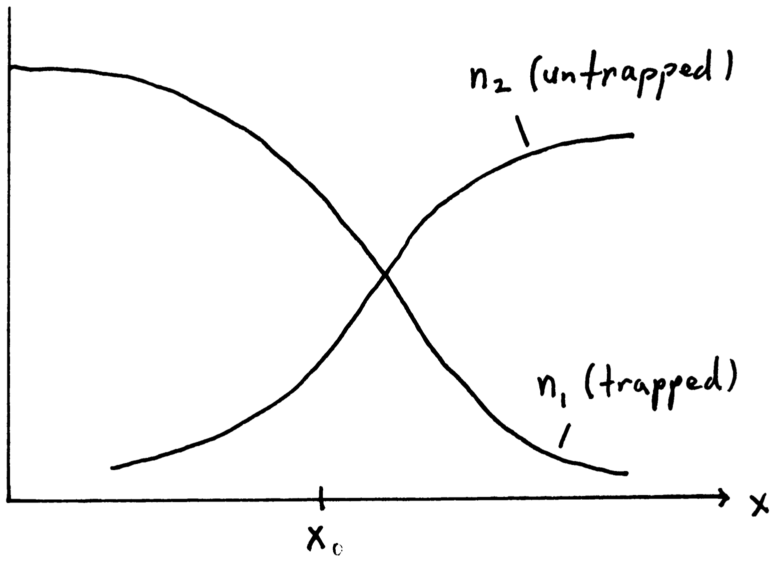

Figure 3: Equilibrium for ion-ion instability.

3. Lower-hybrid-drift instability

The lower-hybrid-drift instability was first proposed by Huba et al. (1977) as a source of anomalous resistivity for reconnection in the earth's magnetotail. Two factors in favor of this instability are (1) the mode can be excited in relatively broad current sheets ($\lambda \lessdot (m_i/m_e)^{1/4} \rho_i$), and (2) the mode is insensitive to the temperature ratio T_e/T_i. Both of these factors should be contrasted to, say, the requirements for the ion acoustic instability. A subsequent study determined that turbulence observed in the distant magnetotail was consistent with the occurrence of the lower-hybrid-drift instability (Huba et al., 1978). However, a problem with this instability (as it applies to a reconnection process) is that the mode is damped in a high β plasma ($\beta >> 1$) because of an electron ∇B drift-wave resonance. Thus, based upon both a local and nonlocal linear analysis (Huba et al., 1980), the instability is stable in the near vicinity of the null point.

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Although this result is unfavorable in directly providing an anomalous resistivity in the diffusion region, the evolution of the magnetic field in the presence of a resistivity based upon the nonlocal mode structure of the lower-hybrid-drift instability has been investigated (Drake et al., 1981). In this regard, a 1D transport equation for the magnetic field has been developed for an arbitrary resistivity profile in a field-reversed plasma. The equation is given by

$$\frac{\partial B}{\partial t} + \frac{cE}{B}\frac{\partial B}{\partial x} - \frac{2B}{B^2+B_\ell^{\,2}}\frac{\partial}{\partial x}\nu_{an}\rho_{es}^{\,2} B\frac{\partial B}{\partial x} = \frac{2B\,B_\ell}{B^2+B_\ell^{\,2}}\frac{\partial B_\ell}{\partial t} \qquad (1)$$

where B_ℓ = B (outer boundary) and $\rho_{es}^2 = \rho_e^2(T_i/T_e)$. On the LHS of Eq. (1) the first term represents the time rate of change of the magnetic field, the second term represents convection because of the inductive electric field E, and the third term represents diffusion based upon an arbitrary collision frequency ν_{an}. The RHS side of Eq. (1) contains the effect of a time-varying boundary field.

We have solved Eq. (1) numerically (Drake et al., 1981). A resistivity model such that $\eta \propto B^2$ was chosen; this model has the feature that $\eta = 0$ at the neutral line, but $\eta \neq 0$ away from the neutral line. The results of this work are illustrated in Fig. 4. The initial magnetic field (Fig. 4a) and current density (Fig. 4b) profiles are labeled $\tau = 0$; the profiles at a later time are labeled $\tau = 0.2$. It is found that magnetic flux is transported towards the neutral line and that the current density increases at the neutral line which is due to a diffusion process. This leads to the possibility that waves can subsequently penetrate to the neutral region during the nonlinear evolution of the field-reversed plasma. Such an evolution has been observed in particle simulations of field-reversed plasmas (Winske, 1981; Tanaka and Sato, 1981). However, these simulations used unrealistic mass ratios and it is unclear at this time whether or not wave penetration occurs using realistic mass ratios (Quest, private communication).

Finally, recently a 2D mode coupling nonlinear theory of the lower-hybrid-drift instability has been developed (Drake et al., 1983). This theory is consistent with both laboratory measurements of the instability as well as with computer simulations. An important result from this new theory is an estimate of the anomalous resistivity associated with the turbulence: $\nu_{an} \simeq 2.4(\rho_i/\lambda)^2\omega_{\ell h}$. This value of ν_{an} corresponds to a magnetic Reynolds number of $R_m \simeq 0.5\,(m_i/m_e)^{1/2}(\lambda/\rho_i)^3$. Thus, it is found that the lower-hybrid-drift instability only provides significant anomalous transport for current sheets such that $\lambda \simeq \rho_i$. Also, a discussion of this instability as it applies to substorm dynamics is given in Huba et al. (1981).

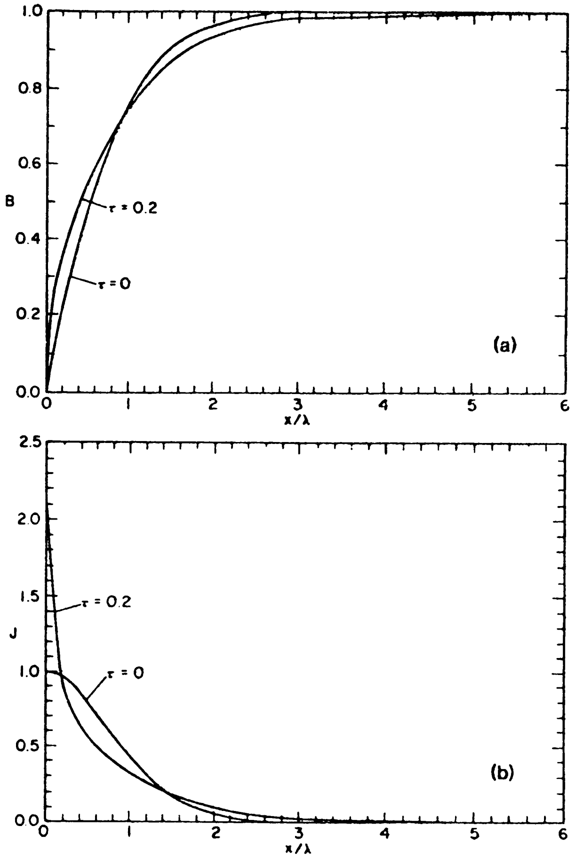

Figure 4: Time evolution of B and J based upon Eq. (1).

V. CONCLUDING REMARKS

It is well known that microinstabilities can affect the dynamic evolution of plasmas through wave-particle interactions (i.e., scattering) and cause anomalous diffusion, momentum transfer and energy exchange. The purpose of this review is to briefly discuss several instabilities that have been proposed as anomalous transport mechanisms in current sheets. The focus has been on reversed magnetic field configurations (Fig. 2a), as they relate to collisionless reconnection processes, since the presence of microturbulence in the diffusion region can influence the hydrodynamic flows. However, the stability analysis of waves in the diffusion region is difficult and simplifying assumptions are made, as noted in Section II.

The two "favored" instabilities are the ion acoustic instability and lower-hybrid-drift instability. The ion acoustic instability can be excited in the null field region but requires quite thin current sheets ($\lambda \lesssim$ few (c/ω_{pe})) and is more easily excited in hot electron plasmas ($T_e \gg T_i$). Although it has been observed in laboratory reconnection experiments where these conditions can be met, its occurrence in relevant space plasmas is rather unlikely (e.g., the earth's magnetotail). On the other hand, the lower-hybrid-drift instability has received considerable attention since it can be excited in broader current sheets ($\lambda \sim \rho_i$) and is relatively insensitive to T_e/T_i. However, the waves are strongly damped close to the null region. In a dynamic situation (e.g., forced reconnection), lower-hybrid-drift wave turbulence may penetrate the null region, but this result is tentative at this time. Nonetheless, even if this turbulence does not penetrate the null region, it is likely to exist over a substantial portion of the current sheet and can strongly affect plasma flow in the regions where the mode is unstable. One possibility is that this instability may limit the width of current sheets to $\lambda \sim \rho_i$ and inertial effects may be dominant in the null region (Coroniti, private communication).

We emphasize that a simplified plasma and field configuration has been used. It is possible that other instabilities may be excited which depend upon non-Maxwellian distribution functions which contain, say, beams and anisotropies. In this regard, laboratory experiments and in situ space observations may indicate more appropriate distribution functions.

Finally, as noted in the introduction, it is crucial to self-consistently incorporate plasma turbulence in the dynamic evolution of collisionless reconnection. This is an exceedingly difficult problem which, perhaps, may only be answered by 3D particle or hybrid simulations, which in themselves are also enormously difficult and beyond present day computational facilities. Maybe our grandchildren will finally solve the problem.

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DISCUSSION

Van Hoven: Would you comment on the effects of the addition of B_y to your model, so that it has field shear? Does one have different spatial structure or different instabilities?

Huba: Finite B_y introduces magnetic shear into the equilibrium model. A study of this situation is given in Huba et al., J. Geophys. Res. 87, 1697 (1982). Basically, magnetic shear has a stabilizing influence on the lower-hybrid-drift instability (and instabilities in general), and acts to inhibit penetration of the mode toward the neutral line.

Migliuolo: The addition of a y-component of the equilibrium B-field keeps β low in the central region. This might make some of the aforementioned modes (e.g. ion-acoustic) more effective in producing η_{an}.

Huba: Although a y-component of $\underset{\sim}{B}$ may keep β low in the central region, it introduces magnetic shear into the equilibrium, which is a stabilizing influence. (See reply to Van Hoven.)

Vasyliunas: Nearly all of the instabilities discussed, with the exception of lower-hybrid-drift, occur only when the thickness of the current sheet is comparable to or less than c/ω_{pe}, but on this scale the inertial terms in the generalized Ohm's law dominant and their neglect is rather questionable.

Huba: This point is discussed in Coroniti and Eviatar (1977). It is not clear that inertial terms would be dominant over the anomalous resistivity provided by, say, the ion acoustic instability. However, I agree they should be included for self-consistency.

D. Smith: Could you go into more detail on how magnetic field is transported toward the neutral line?

Huba: The transport of magnetic flux towards the neutral line in the presence of an anomalous collision model based upon the lower-hybrid-drift instability is simply a diffusion process. It is evident in the 3rd term on the LHS of Eq.(1) which is the 1D transport equation for B.

Hasegawa: MHD equilibrium requires the presence of ∇p rather than $\nabla n = 0$?

Huba: The analysis of the lower-hybrid-drift instability is based upon $p = nT$. If $\nabla n = 0$, then for $\nabla T \neq 0$. The lower-hybrid-drift instability can be excited when $\nabla n = 0$ and $\nabla T \neq 0$.

Coppi: In the theory of magnetic reconnection it is necessary to couple the consideration of microscopic (kinetic) effects with those of the macroscopic magnetic configuration. In fact, the theory of tearing modes in collisionless regimes for sheared magnetic field configurations shows that these tend to become stable, and this could not be foreseen without carrying out a complete analysis. Therefore it is probably premature, on the basis of the state of the theory you presented, to pass a judgement on what is adequate to explain the reconnection processes that appar to occur in the Earth's magnetotail.

Huba: I agree that a self-consistent theory which couples microturbulence to the macroscopic evolution of the plasma is needed. I have tried to emphasize this point in my paper, although the purpose of the article is to simply review the linear and nonlinear properties of various instabilities possibly relevant to reconnection processes.