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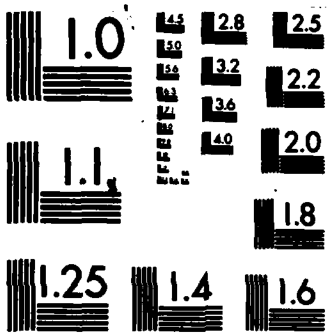

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NRL Memorandum Report 52[illegible]

Fast Collisionless Tearing in an Anisotropic Neutral Sheet

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February 6, 1984

This research was sponsored by the National Aeronautics and Space Administration and the Office of Naval Research.

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84 02 07 123

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 5240	2. GOVT ACCESSION NO. AD-A137623	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FAST COLLISIONLESS TEARING IN AN ANISOTROPIC NEUTRAL SHEET		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. Chen,* P.J. Palmadesso, J.A. Fedder, and J.G. Lyon		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375		10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS W-15494; 61153N; RR-033-02-44; 47-1982-0-3; 47-0884-0-3
11. CONTROLLING OFFICE NAME AND ADDRESS National Aeronautics & Space Admin. Washington, DC 20546	Office of Naval Research Arlington, VA 22203	12. REPORT DATE February 6, 1984 13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

*Present address: Science Applications, Inc., McLean, VA 22102

This research was sponsored by the National Aeronautics and Space Administration and the Office of Naval Research.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tearing instability
Anisotropic neutral sheet
Magnetotail

→ This document studies

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

The collisionless tearing mode in a neutral sheet is studied in the presence of ion temperature anisotropy using Vlasov description for both ions and electrons. It is found that the growth rate of the instability is significantly enhanced if $T_{i\perp}/T_{i\parallel} > 1$, where the symbols $\perp$ and $\parallel$ refer to the directions perpendicular and parallel to the equilibrium magnetic field. For typical magnetotail parameters with modest temperature anisotropy, it is shown that the linear e-folding time is reduced to a small fraction of the time delays believed to precede the onset of reconnection.

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20. ABSTRACT (Continued)

This enhancement of the growth rate is due to the Lorentz force acting on the ions that cross the neutral plane and that traverse beyond the conventional electron tearing layer.

CONTENTS

FAST COLLISIONLESS TEARING IN AN ANISOTROPIC NEUTRAL SHEET

1. INTRODUCTION

The isotropic collisionless tearing mode (Furth, 1962; Pfirsch, 1962) has been under extensive investigation for the past few decades (Laval et al., 1965; Schindler, 1966; Schindler and Soop, 1968; Dobrowolny, 1968; Biskamp and Schindler, 1971; Quest and Coroniti, 1981). In particular, it was suggested (Coppi et al., 1966) as a possible mechanism for magnetic field line reconnection in the magnetosphere (Dungey, 1961). The tearing mode may also be relevant to the dayside magnetopause (e.g., Greenly and Sonnerup, 1981; Quest and Coroniti, 1981).

The central importance of the tearing mode is that the growth rate of the instability is believed to provide a measure of the time delay for the onset of reconnection after the interplanetary magnetic field turns southward. One difficulty in identifying the conventional isotropic collisionless tearing mode as a possible mechanism for reconnection is that the instability is a weak one. For example, using the results of Dobrowolny (1968), the electron tearing growth time is estimated to be of the order of 1 hour for the tail region, which is too long to have any role. However, in a collisionless plasma, the motion of particles parallel to the magnetic field is decoupled from the perpendicular motion and temperature (and pressure) anisotropy is likely to exist (Crooker and Siscoe, 1977; Cowley, 1978).

Laval and Pellat (1968) used an energy principle analysis to show that collisionless tearing mode properties can be strongly modified by weak anisotropy. In this work, however, the eigenmode structure was not studied and quantitative estimates of the growth rate were not given. Recently, Chen and Davidson (1981) carried out a Vlasov-fluid analysis for a field-reversed ion layer at marginal stability using approximate orbits. It is

Manuscript approved October 19, 1983.

found that slight anisotropy ($T_{i\perp}/T_{i\parallel} > 1$) can increase the range of unstable wavenumbers of the tearing mode in an ion layer, indicating that the magnetopause and magnetotail properties may be affected significantly by anisotropy. Here the symbols $\perp$ and $\parallel$ refer respectively to the directions perpendicular and parallel to the equilibrium magnetic field. More recently, Basu and Coppi (1982) studied a fluid-like "field swelling" instability in an anisotropic plasma. This analysis is local and is based essentially on the fluid equations so that it is difficult to assess its applicability to the tearing mode which is due to the large orbits crossing the neutral line.

Because the previous works have not been able to provide the dispersion relation, the importance of the anisotropy effects has not been appreciated. In this paper, we calculate the anisotropic dispersion relation and show that the tearing mode growth rate for a collisionless neutral sheet can be strongly enhanced if the temperature distribution is anisotropic $(T_\perp > T_\parallel)$. In light of the new results, we reconsider some aspects of the reconnection processes in the open magnetosphere. However, the detailed mathematical treatment of the plasma physics aspects is not appropriate here and will be published elsewhere (Chen and Palmadesso, 1983). As a general remark, we note that the real magnetotail has a small normal component of the magnetic field which may be stabilizing to collisionless tearing mode because the electrons can be magnetized (Galeev and Zelenyi, 1976; Lembege and Pellat, 1982). However, ions may still be unmagnetized, giving rise to an "ion tearing mode" (Schindler, 1974). In addition, pitch angle scattering may tend to destabilize the mode (Coroniti, 1980) as well as isotropize electron anisotropy. In the present work, we do not include the normal field or pitch angle scattering.

Because the above effects tend to affect primarily the electrons, we will take the electrons to be isotropic and include only anisotropic ions.

2. ANISOTROPIC TEARING-MODE INSTABILITY

The perturbation considered has the form $\psi(x,z,t) = \hat{\psi}(z)\exp(ikx-i\omega t)$. The wavevector $\underline{k} = k\underline{x}$ is parallel to the equilibrium magnetic field $\underline{B}_o(z) = B_o(z)\underline{x}$, which is generated self-consistently by the current density $\underline{J}_o = J_o\underline{y}$. For the tearing mode, we have $\omega << \omega_{ci}$ where ω_{ci} is the ion cyclotron frequency in the asymptotic field $B_o = B_o(z \rightarrow \infty)$. In addition, for the parameters of interest, we also have $\omega << kv_{th}$ where v_{th} is the thermal velocity of the particles. In this paper, we adopt for both ions and electrons ($j = i,e$) Harris-type equilibrium distribution functions given by

$$f_{oj}\left(H_{\perp j} - V_j P_{yj}, H_{\parallel j}\right)$$

$$= \frac{\hat{n}_o}{2\pi T_{\perp j}/m_j} \frac{1}{\sqrt{2\pi T_{\parallel j}/m_j}} \exp\left[-\frac{1}{T_{\perp j}}\left(H_{\perp j} - V_j P_{yj}\right)\right] \exp\left(-\frac{1}{T_{\parallel j}} H_{\parallel j}\right), \qquad (1)$$

where $H_{\perp j} = (m_j/2)(v_y{}^2 + v_z{}^2)$, $P_{yj} = m_j v_j + (q_j/c)A_y{}^0(z)$, $H_{\parallel j} = (m_j/2)v_x{}^2$, V_j = constant is the mean velocity of the species j, and $A_y{}^0(z)$, is the vecter potential for the equilibrium magnetic field. The electrostatic field is taken to be zero in the frame of the neutral sheet and charge neutrality will be assumed. Then the self-consistent equilibrium quantities are well-known and are given by $n_o(z) = n_o \text{sech}^2(z/\delta)$ and $B_x{}^0(z) = B_o \tanh(z/\delta)$, where $B_o \equiv \left(8\pi\hat{n}_o T_\perp\right)^{1/2}$, $T_\perp \equiv T_{i\perp} + T_{e\perp}$ and

$$\delta \equiv \left(\frac{c^2 T_\perp}{2\pi\hat{n}_o}\right)^{1/2} \frac{1}{e\left(V_i - V_e\right)} . \qquad (2)$$

Using the method of characteristics, the linearized Vlasov distribution function for each species can be written as

$$f_{1j} = \frac{q_j \beta_j}{T_{j\perp}} f_{oj} \psi - \frac{i\omega q_j}{T_{j\perp}} f_{oj} Q_y + \frac{ikq_j}{T_{j\perp}} \left(1 - \frac{T_{j\perp}}{T_{j\parallel}}\right) f_{oj} v_x Q_y \qquad (3)$$

where

$$Q_y \equiv -\frac{1}{c} \int_{-\infty}^{t} dt' v_y' \psi. \qquad (4)$$

Here, $\beta_j \equiv V_j/c$, c is the speed of light, and $\psi(x,z,t) \equiv A_{1y}(x,z,t)$ is the perturbed vector potential. In equation (3), use has been made of $\partial/\partial t \to -i\omega$ and $\partial/\partial x \to ik$. In obtaining equations (3) and (4), we have used $\phi \ll (\omega/kv_{th})(v_y/c)\psi$ which is a consequence of charge neutrality at low perturbation frequencies (Dobrowolny, 1968). Here, ϕ is the perturbed scalar potential. Using equation (3) in Ampere's law, we obtain

$$\frac{d^2\hat{\psi}}{dz^2} - k^2\hat{\psi} = -\frac{4\pi}{c} \sum_j q_j \int d^3\underline{v}\, v_y f_{1j} \qquad (5)$$

where $\hat{\psi}(z) \equiv \psi(x,z,t)\exp(-ikx+\omega t)$.

In the isotropic limit, $T_{j\perp}/T_{j\parallel} = 1$, the last term of equation (3) vanishes and the isotropic results are recovered. For the anisotropic case, estimating v_x by the typical thermal velocity v_{th}, we see that the second term is smaller than the last term by approximately $\omega/(kv_{th}) \ll 1$ so that the anisotropy term is dominant unless the degree of anisotropy is small. In order to evaluate Q_y and f_{1j} quantitatively, we note that the component v_y is nearly constant for a typical particle in the inner regions ($|z| < d_j$, j = i, e) where the magnetic field is weak and that a typical particle is magnetized in the outer regions ($|z| > d_j$). Here, we take $d_i \equiv \sqrt{a_i \delta/2}$ and $d_e \equiv \sqrt{2a_e \delta}$, where a_j is the Larmor radius of a thermal particle of species j. These approximatiobns are intended to model the various particle orbits as described by, for example, Sonnerup (1971). In addition, $\hat{\psi}(z)$ is assumed to be nearly constant (constant-ψ approximation) in the inner regions. In the outer regions $|z| > d_j$, the particles execute the usual ∇B drift motion.

Using the above approximations, after some algebra, we obtain for each species in the respective inner regions ($|z| < d_j$)

$$Q_y^{in} = i\, c^{-1} v_y \hat{\psi}(z)(kv_x - \omega)^{-1} \exp(ikx - i\omega t) \tag{6}$$

and in the respective outer regions ($|z| > d_j$)

$$Q_y^{out} = i\, c^{-1} V_D^{\,j}\, \hat{\psi}(z)(kv_x - \omega)^{-1} \exp(ikx - i\omega t) \tag{7}$$

The quantity $V_D^{\,j}$ is the usual $\underline{\nabla} B$ drift velocity in the y-direction. Using equations (3), (5), (6) and (7), it is clear that equation (5) is an eigenvalue equation for $\hat{\psi}(z)$, subject to the conditions that its first derivative $(\partial\hat{\psi}/\partial z)$ vanish asymptotically ($|z| \to \infty$) and that the logarithmic derivative be continuous at $|z| = d_e$ and $|z| = d_i$. However, unlike the conventional isotropic tearing-mode calculations in neutral sheets (see for example, Dobrowolny, 1968) in which the "inner" solution for $|z| < d_e$ is matched to the "outer" solution for $|z| > d_i$, it is found that the dispersion relation for the anisotropic tearing-mode is critically affected by the ion orbits in the "intermediate" region $d_e \lesssim |z| \lesssim d_i$. Therefore, the eigenvalue equation (5) must be solved in the above three regions. For the inner region, an analytical solution can be obtained. In the intermediate and outer regions, the equation is solved numerically. The resulting dispersion relation, obtained by matching the logarithmic derivative of $\hat{\psi}$ at $z = d_e$ and $z = d_i$ (three-region approximation), is shown in Figure 1 for several values of $T_{i\perp}/T_{i\parallel}$ with $a_i/\delta = 0.1$.

The first point to note is that γ/ω_{ci} and hence the associated values of γ/kv_i and γ/kv_e are all substantially less than unity, justifying the low frequency approximations a posteriori. Another point to note is that curve b for the isotropic case is nearly equal to the conventional two-region result with the present three-region growth rates being slightly smaller. This reduction in γ can be traced to the $\underline{\nabla B}$ contributions. As $\alpha_i \equiv T_{i\perp}/T_{i\parallel}$ is increased, the growth rate and the range of unstable k numbers both increase substantially. For example, the maximum growth rate for $\alpha_i = 1.5$ is $\gamma = 2.2 \times 10^{-3} \omega_{ci}$ compared with the isotropic maximum growth rate $\gamma = 1.9 \times 10^{-4} \omega_{ci}$ for the same parameters, an enchancement by a factor of 10. The wavelength at maximum γ is reduced to roughly 2.7δ from 27δ. For $\alpha_i < 1$, even a small deviation from isotropy strongly stabilizes the mode as shown by curve a of Figure 1. This latter behavior is consistent with the conclusion of Laval and Pellat (1968). Physically, the anisotropy effects discussed are due to the Lorenz force which is similar to the mirror forces (the third term of equation (3)). Note also that Hill (1975) found that the magnetic merging is enhanced when $p_\perp > p_\parallel$.

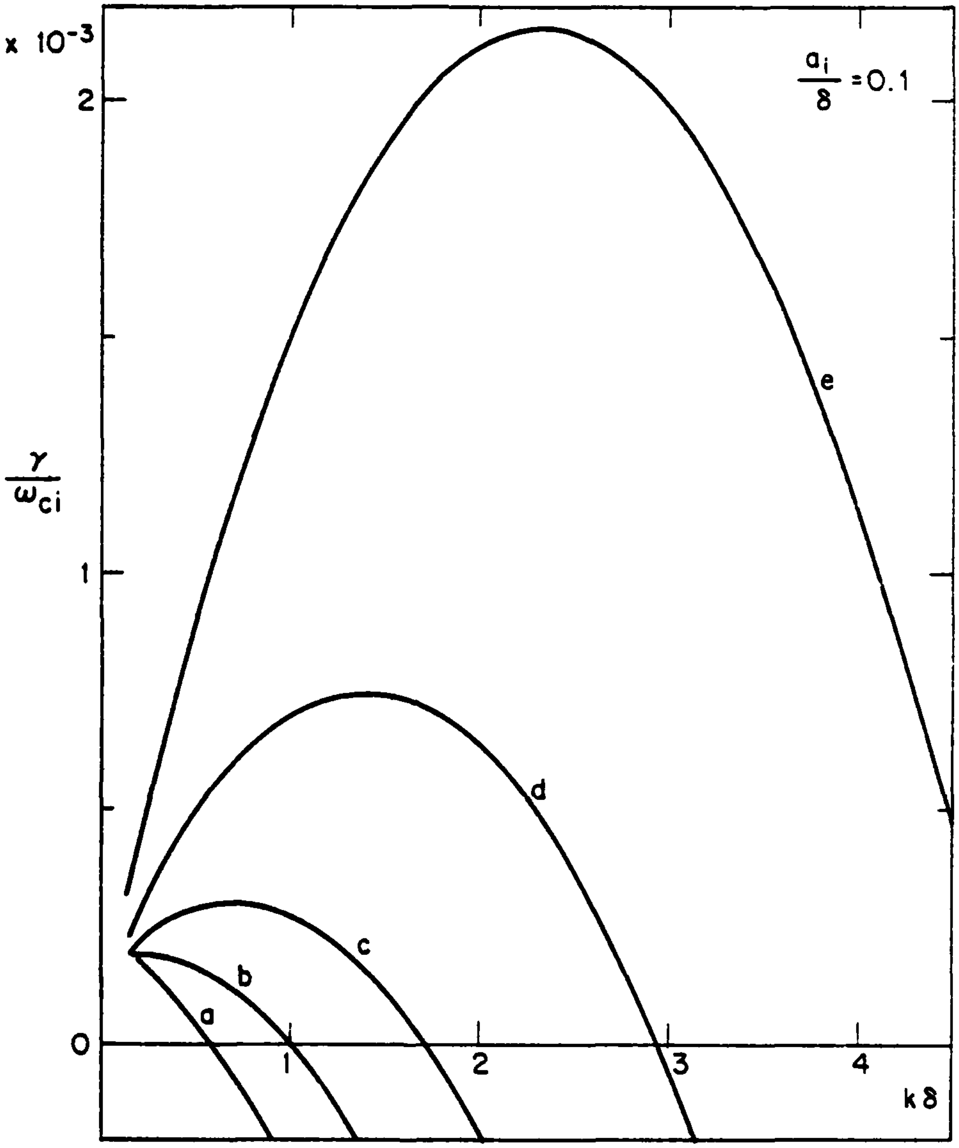

Fig. 1. Normalized growth rate (γ/ω_{ci}) versus kδ with $a_i/\delta = 0.1$ and isotropic electrons. The value of $T_{i\perp}/T_{i\parallel}$ is (a) 0.9, (b) 1.0, (c) 1.1, (d) 1.25 and (e) 1.5. The curves are not completed near kδ = 0 because a number of approximations break down for k → 0.

3. DISCUSSION

Two regions where the preceding results may be relevant are the neutral regions of the magnetotail and the dayside magnetopause. In this regard, we note that the need to include temperature anisotropy in these regions has been pointed out (Crooker and Siscoe, 1977; Cowley, 1978). We will use some parameters suitable for the neutral region in the tail for illustration. For example, for 1keV ions, $a_i/\delta = 0.1$, $T_{i\perp}/T_{e\perp} = 2$ and $B_o = 20\gamma$, we obtain $\omega_{ci} \simeq 1.9\mathrm{sec}^{-1}$ and Figure 1 (curve b) yields the minimum e-folding time $(\gamma_{max}^{-1}) \simeq 45$ minutes for the isotropic case. If $\alpha_i = 1.25$, then $(\gamma_{max}^{-1}) \simeq 12$ minutes. For $\alpha_i = 1.5$, we have $(\gamma_{max}^{-1}) \simeq 4$ minutes, a reduction by more than one order of magnitude. This shows that, in the presence of even small to modest ion temperature anisotropy, the e-folding time scale is a small fraction of the delay time of roughly 30 minutes for the onset of reconnection. We, therefore, conclude that the anisotropic collisionless tearing mode may indeed play an important role in reconnection processes in the magnetosphere. It is important to note that no classical or anomalous resistivity is used in our calculation. Further increase in α_i yields even greater enhancement in the growth rate. However, the approximations used in the analysis begin to break down for much larger α_i so that we are not able to make quantitative statements for large degrees of anisotropy.

So far, the anisotropic tearing mode results have been considered in the context of the tail region. In the neutral region of the dayside magnetopause, a_i/δ may be nearly unity, which is outside the regime of validity of the present analysis. However, we expect qualitatively similar effects to occur. Note also that only the linear regime has been investigated and we cannot draw definitive conclusions concerning the possible magnetic island formation. However, we speculate that the saturation level in the presence of anisotropy is greater than in the absence of anisotropy. Subsequent to the work of Chen and Palmadesso (1982), numerical simulations have been performed using a one-component plasma (hot ions and cold electrons) (Ambrosiano and Lee, 1983) and the preliminary results indicate that the growth rate and the saturation amplitudes both increase substantially as α_i is increased from unity.

As discussed in Section 1, the magnetotail possesses a number of features such as the weak normal component of the magnetic field and pitch angle scattering that are not included in the present analysis. So far, these modifications have been applied to the isotropic tearing mode in the literature. In view of the fact that anisotropic tearing mode completely dominates the isotropic case, we suggest that tearing instability in the presence of anisotropy is the more relevant perturbation to investigate and that the above modifications should be considered for the anisotropic case. Moreover, since the enhancement of the growth rate is primarily due to the large ion orbits, we expect qualitatively similar effects to persist even if the above refinements are included.

ACKNOWLEDGMENT

This research was supported by NASA and ONR.

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