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Tearing modes at the magnetopause

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Abstract. It is shown that the shear flow present in the magnetopause current layer can destabilize the tearing modes depending upon the Mach number profiles. Using a variational principle, an heuristic stability criterion based on the form of the Mach number profile is obtained. This criterion could be used as a handy tool to search for tearing mode instability of a given magnetopause equilibrium with shear flow. The Doppler shifted magnetic structures produced by the tearing modes would be observable at ultralow frequencies in the range of ~ 5 - 650 mHz in the satellite frame of reference.

1. Introduction

Low-frequency electromagnetic fluctuations at the magnetopause are believed to play an important role in the processes related to energy transfer from the solar wind to the magnetosphere [*Paschmann et al.*, 1978; *Thorne and Tsurutani*, 1991; *Song et al.*, 1993; *Lakhina et al.*, 1993]. Shear flow can affect the stability of the magnetopause current sheet in two important ways. First, excitation of tearing modes may be influenced, and second, Kelvin-Helmholtz type instabilities may be excited. Kelvin-Helmholtz instabilities driven by the shear flow in the magnetopause current layer have been suggested as a possible candidate for exciting the low-frequency turbulence at the magnetopause [*Miura and Pritchett*, 1982; *Rajaram et al.*, 1991; *Parhi and Lakhina*, 1993]. The presence of shear flow can also affect the excitation of tearing mode instability at the magnetopause [*Lakhina and Schindler*, 1983a,b]. Tearing mode instability can induce large-scale topological changes in the magnetic field configuration, and thereby it may control mass and energy transfer from the solar wind to the magnetosphere, for example, by exciting time dependent reconnection and flux transfer events (FTEs). Tearing-produced magnetic structures convected with the plasma bulk flow are likely to be manifested as some kind of ULF waves [*Greenly and Sonnerup*, 1981; *Lakhina and Schindler*, 1983a,b].

There are several studies of tearing modes relevant to the magnetopause boundary layer [*Drake and Lee*, 1977; *Galeev et al.*, 1986; *Quest and Coroniti*, 1981a,b]. Above studies did not take into account the presence of shear flow in the magnetopause boundary layer. Recently, there have been several studies on the effects of shear flow on the resistive tearing modes [*Hoffmann*, 1975; *Paris and Sy*, 1983; *Pu et al.*, 1990; *Chen and Morrison*, 1990] as well as on collisionless tearing modes [*Lakhina and Schindler*, 1983a,b; *Greenly and Sonnerup*, 1981; *Wang and Ashour-Abdalla*, 1992; *Kuznetsova et al.*, 1994]. However, conflicting results regarding the effects of shear flow on the tearing modes have been reported. For example, the shear flow was found to have a destabilizing effect [*Paris and Sy*, 1983; *Lakhina and Schindler*, 1983a; *Pu et al.*, 1990], a stabilizing effect [*Greenly and Sonnerup*, 1981; *Wang and Ashour-Abdalla*, 1992; *Kuznetsova et al.*, 1994], and either a stabilizing or a destabilizing effect [*Hoffman*, 1975; *Chen and Morrison*, 1990] on the tearing mode instability.

We investigate the excitation of the tearing modes in the presence of shear flow in the magnetopause boundary layer. We consider the neutral point tearing, that is, the case of $B_y = 0$, where B_y is the y (or dawn-dusk) component of the magnetic field $\mathbf{B}_0$. We show that Mach number profile, and not the velocity profile alone, decides the effect of shear flow on the tearing modes. This study, thus, resolves the confusion about the effect of shear flow on the tearing modes. We find that the magnetic structures produced by the tearing modes would be Doppler shifted by the flow in the range of ULF wave frequencies.

2. The Model for Tearing Modes

We treat the magnetopause as a plane collisionless current sheet [*Harris*, 1962]. The sheet current flows along the y axis and produces a magnetic field:

$$\mathbf{B}_0(z) = B_0 \tanh z/L\,\mathbf{x}, \qquad (1)$$

where L is the half thickness of the sheet, and $\mathbf{x}$ denotes the unit vector in the x direction. The magnetopause current sheet contains the sheared bulk flow parallel to magnetic field:

$$\mathbf{V}_0(z) = V_0(z)\,\mathbf{x}. \qquad (2)$$

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Following *Drake and Lee* [1977] and *Lakhina and Schindler* [1983a], we use MHD in the "outer region" (i.e., $z \geq \delta_e$), and a kinetic approach in the "inner region" (i.e., $z \leq \delta_e$). Here $\delta_j = (\rho_j L)^{1/2}$, where $\rho_j = V_{Tj}/\Omega_j$ is the Larmor radius, $\Omega_j = eB_0/m_j c$ is the cyclotron frequency, and $v_{Tj} = (T_j/m_j)^{1/2}$ is the thermal speed of the jth species, with $j = e$ for electrons, and i for the ions.

For the linear stability analysis we take every perturbed quantity g as:

$$g = g(z)\,\exp[-i\,\omega\,t + i\,k\,x]. \tag{3}$$

Then, the eigenmode equation for the perturbed vector potential $\mathbf{A} = A\,\hat{y}$, in the external region can be written [*Lakhina and Schindler*, 1983a; *Wang and Ashour-Abdalla*, 1992] as,

$$\frac{d}{d\bar{z}}(1-M^2)\frac{d}{d\bar{z}}A - (1-M^2)\left(\bar{k}^2 + \frac{1}{B_0(\bar{z})}\frac{d^2 B_0(\bar{z})}{d\bar{z}^2}\right)A + \frac{d}{d\bar{z}}M^2\frac{1}{B_0}\frac{d}{d\bar{z}}B_0(\bar{z})A = 0, \tag{4}$$

where $\bar{z} = z/L$, $\bar{k} = Lk$, etc., and we have defined the Alfvén Mach number $M = V_0(z)/V_A(z)$, where $V_A(z) = B_0(z)[4\pi\rho_0(z)]^{-1/2}$ is the Alfvén speed.

We consider the Mach number profile:

$$M^2 = 1 - \epsilon\,\cosh^{-2m}(\bar{z}), \tag{5}$$

where $0 < \epsilon \leq 1$. For this Mach number profile, (4) has an exact analytic solution [*Lakhina and Schindler*, 1983a] for the external region which satisfies the boundary condition $A(\bar{z} \to \infty) = 0$, namely,

$$A = \frac{C_1\,\Gamma(\nu+\sigma+1)P_\nu^{-\sigma}(\tanh\bar{z})\cosh^m(\bar{z})}{\Gamma(\nu-\sigma+1)\,\cos\sigma\pi}, \tag{6}$$

where $\nu = (1+m)$, $\sigma = (\bar{k}^2 + m^2)^{1/2}$, and C_1 is a constant.

In the inner region ($\bar{z} \leq \bar{\delta}_e$), the particle orbits can be treated as essentially unmagnetized and the bulk flow velocity may be taken as approximately constant, that is, $\mathbf{V}_0(z) = u\,\mathbf{x}$. However, our special choice of the above Mach number profile would correspond to taking $u = 0$. Then, the eigenmode equation for A in the inner mode is found to be,

$$\left[\frac{d^2}{d\bar{z}^2} - (\bar{k}^2 - 2\,\mathrm{sech}^2\bar{z})\right]A = -i\sqrt{\frac{\pi}{8}}\frac{\omega\,L^2\,\mathrm{sech}^2\bar{z}}{kv_{Te}\rho_e^2(1+T_i/T_e)}\,A. \tag{7}$$

Taking $\mathrm{sech}^2\bar{z} = 1$, the inner region solution satisfying the boudary condition that $A(\bar{z}=0) = A_0$ and $A'(\bar{z}=0) = 0$, can be written as,

$$A = A_0\cosh\alpha\,\bar{z}, \tag{8}$$

$$\alpha^2 = \left[\bar{k}^2 - 2 - i\sqrt{\frac{\pi}{8}}\frac{\omega L^2}{kv_{Te}\rho_e^2(1+T_i/T_e)}\right] \tag{9}$$

The dispersion relation for the tearing mode is obtained by matching the inner region and the outer region solution for A at $\bar{z} = \bar{\delta}_e$. Then, equating A'/A from the inner and outer solutions at $\bar{z} = \bar{\delta}_e$ we get the tearing mode dispersion relation:

$$\omega_r = ku = 0, \tag{10}$$

$$\gamma = \left(\frac{8}{\pi}\right)^{\frac{1}{2}}\left(\frac{\rho_e}{L}\right)^{3/2} k\,v_{Te}(1+T_i/T_e)\,\frac{[(1+2m-\bar{k}^2)\Lambda_1 - 2m\bar{\delta}_e\Lambda_2]}{[\Lambda_2 + \bar{\delta}_e(\nu^2-\sigma^2)\Lambda_1]}, \tag{11}$$

where,

$$\Lambda_1 = \Gamma(\sigma/2+\nu/2)\,\Gamma(\sigma/2-\nu/2+1/2),$$
$$\Lambda_2 = 2\,\Gamma(\sigma/2+\nu/2+1/2)\,\Gamma(\sigma/2-\nu/2+1). \tag{12}$$

For $m = 0$, the dispersion relation becomes identical with the case of no shear flow [*Coppi et al.*, 1966].

Figure 1 shows normalized growth rate γ/Ω_i versus normalized wavenumber $\bar{k} = k\,L$. It is clear that both the growth rate and the range of unstable wave number increase with the increase of shear flow index m (cf. curves 1 to 4). For negative values of m (cf. curve 5 which is for $m = -1$) the mode is stabilized.

The Mach number profile considered here implies $V_0(\bar{z}) \approx V_A(\bar{z}) \gg 1$ for $|\bar{z}| \gg 1$. According to the Harris sheet model, this would lead to flow velocity attaining unphysically large values at large $\bar{z}$. *Lakhina and Schindler* [1983a] showed that for sufficiently large

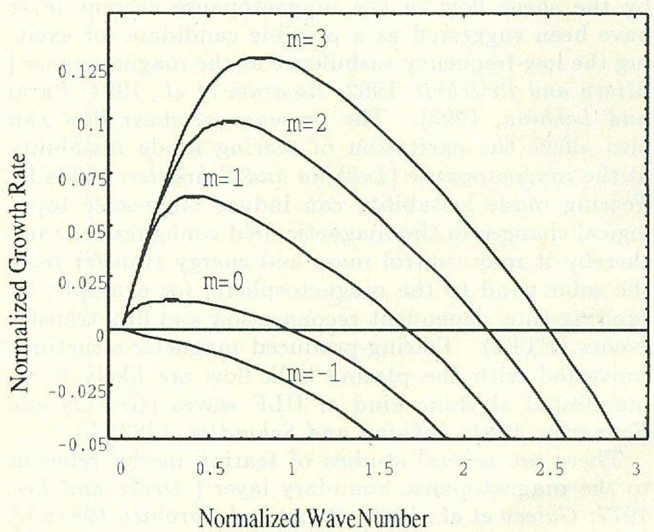

Figure 1. Normalized growth rate γ/Ω_i versus normalized wavenumber kL for the tearing mode instability at the magnetopause for different values of the shear flow index m. Other parameters of the magnetopause current layer are: $T_e = 25$ eV, $T_i = 200$ eV, $\rho_e = 0.34$ km, and $L = 100$ km. For all the curves in this as well as in Figure 2, the value of the parameter ϵ is chosen small (~ 0.01 or less) such that $M^2 > 0$ for atleast $|\bar{z}| \sim 3$.

k, the solution for A attains a peak for $\bar{z} \sim 1$ and then it decays to reasonably small values at distances of $|\bar{z}| \sim 3$. As the flow velocity is also expected to remain sufficiently small at such distances, the results based on the Mach number profile given by (5) would not be seriously affected. Further, in the Harris sheet model of the magnetopause, all of the particles are essentially "trapped" in the sense that they are "isolated" from the magnetosheath and magnetospheric plasmas. By considering either a uniform background cold plasma component, or the particle accessibility as described by *Whipple et al.* [1984], this "isolation" effect, and in turn the divergence in $\mathbf{V}_A(\bar{z})$ or $\mathbf{V}_0(\bar{z})$ at $|\bar{z}| \gg 1$, can be removed. Furthermore, for negative values of m in (5), one must choose ϵ to be sufficiently small so that M^2 remains positive for sufficiently large $\bar{z}$, or at least for $|\bar{z}| \sim 3$, or so as beyond this distance the contribution from the shear flow becomes unimportant for A as well as δW (defined in the next section).

Equation $\nabla \cdot \mathbf{B} = 0$ predicts that the tearing perturbations in B_z and B_x are out of phase by $\pi/2$. Their magnitudes are related by:

$$\left|\frac{B_z}{B_x}\right| = \left|\frac{kB_z}{dB_z/dz}\right| \simeq kL < (1+2m)^{1/2}, \qquad (13)$$

for all $\bar{z}$ except at $|\bar{z}|$=0 and d, where d is the distance at which B_z has a maximum. It is clear that in the presence of shear flow, the ratio $|B_z/B_x|$ can be either less than or greater than unity. For the case of no shear flow, (13) predicts the $|B_z/B_x|$ to be always less than unity which agrees with the interpretation of *Greenly and Sonnerup* [1981].

It is interesting to note that the convection of magnetic tearing structures along the magnetopause could make the tearing modes observable from a single satellite crossing the magnetopause. Following *Greenly and Sonnerup* [1981], the Doppler-shifted frequencies can be calculated from the relation $f_{obs} = kV_C \cos\theta/2\pi$, where V_C is the convection velocity, and θ is the angle between the convection velocity vector, and the x axis which is the direction of the wave vector $\mathbf{k}$. For the convection flow speed of about 200 km s^{-1}, relative velocity between a satellite and the magnetopause $\sim$ 5 - 10 km s^{-1}, and unstable wavenumber $\bar{k} \simeq$ (0.2 - 2.0), L = 100 km, and $\theta = 10° - 85°$, the tearing mode produced magnetic structures would be Doppler-shifted to produce ULF turbulence in the frequency range of 5 - 650 mHz.

3. Energy Principle

We would like to emphasise that the results shown in Figure 1 are for the specific Mach number profile considered here. To resolve the ambiguity regarding the effects of shear flow on the tearing modes, we take recourse to the energy principle.

When the outer region can be treated by incompressible MHD, the eigenmode equations (4) and (7) for A, the perturbed vector potential of the tearing modes, can be cast into the variational form [*Wang and Ashour-Abdalla*, 1992]:

$$\gamma \int_{-\infty}^{\infty} dz\, \frac{\sqrt{\pi}\omega_{pe}^2}{c^2\, k\, v_{Te}}\, |A|^2 = -[\delta W_1 + \delta W_2 + \delta W_3], \quad (14)$$

$$\delta W_1 = \int_{-\infty}^{\infty} dz\,(1-M^2)|\nabla A|^2, \qquad (15)$$

$$\delta W_2 = \int_{-\infty}^{\infty} dz\,(1-M^2)\frac{\frac{d^2 B_0}{dz^2}}{B_0}\,|A|^2, \qquad (16)$$

$$\delta W_3 = \int_{-\infty}^{\infty} dz\,\frac{d}{dz}(1-M^2)\frac{\frac{dB_0}{dz}}{B_0}\,|A|^2, \qquad (17)$$

It is clear from (14) - (17) that for M=0, δW_3=0, $\delta W_1 > 0$ (i.e., a stabilizing term), and hence the only free energy source for the tearing mode instability is the δW_2 term [*Schindler*, 1966]. For the case of $M \neq 0$, it is rather difficult to make a definitive statement about the effect of shear flow on the tearing modes as all the three terms involving M^2 have different signs. However, the structure of (15) - (17) suggests two main possibilities. First, if δW_1 and δW_2 are affected by the $(1-M^2)$ term by nearly the same amount, that is, whereas the stabilizing term δW_1 is reduced by the shear flow, the destabilizing term δW_2 is also reduced by the shearflow from its value when the flow was absent, then the sign of δW_3 term would decide the net effect of the shear flow. Second, if the sum of $(\delta W_1 + \delta W_2) > 0$, that is, the destabilizing term δW_2 decreases faster than the stabilizing term δW_1 in the presence of shear flow, then δW_3 must necessarily be negative for the tearing mode instability. Therefore we expect that the sign of the δW_3 term would decide the overall stability or instability of the tearing modes in the presence of shear flow with $\delta W_3 > 0$ corresponding to a stabilizing effect and $\delta W_3 < 0$ to a destabilizing situation. It is clear from our arguments that this is not a strict criterion in the mathematical sense. It may, however, be useful as an heuristic principle in the search for instability profiles of a given equilibrium with sheared bulk flow properly.

In Figures 2a-2d, we have shown some results obtained by computing $(\delta W_1 + \delta W_2)$ (dotted curves in Figure 2), δW_3 (dash-dot dash curves in Figure 2), and $\delta W = (\delta W_1 + \delta W_2 + \delta W_3)$ (solid curves in Figure 2) from (15) - (17) using the solution given by (6) for A, and the Mach number profile given by (5). It is clear from Figures 2a-2c, which correspond, respectively, to the case of shear flow index m= 1, 2, and 3, that unstable situation $\delta W < 0$ is associated with $\delta W_3 < 0$. From Figure 2d for m = - 1, we notice that $\delta W_3 > 0$ and it corresponds to stability, that is, $\delta W > 0$ in this case. We may emphasize that $\delta W_3 \leq 0$ is only the necessary condition for instability as can be seen from Figures 2a-2d.

For the case of $V_0(z) = V_0 \tanh \bar{z}$, and for the Harris equilibrium, as considered by *Wang and Ashour-Abdalla* [1992] and others, the Mach number profile is:

$$M^2 = M_0^2 \,\mathrm{sech}^2 \bar{z}. \qquad (18)$$

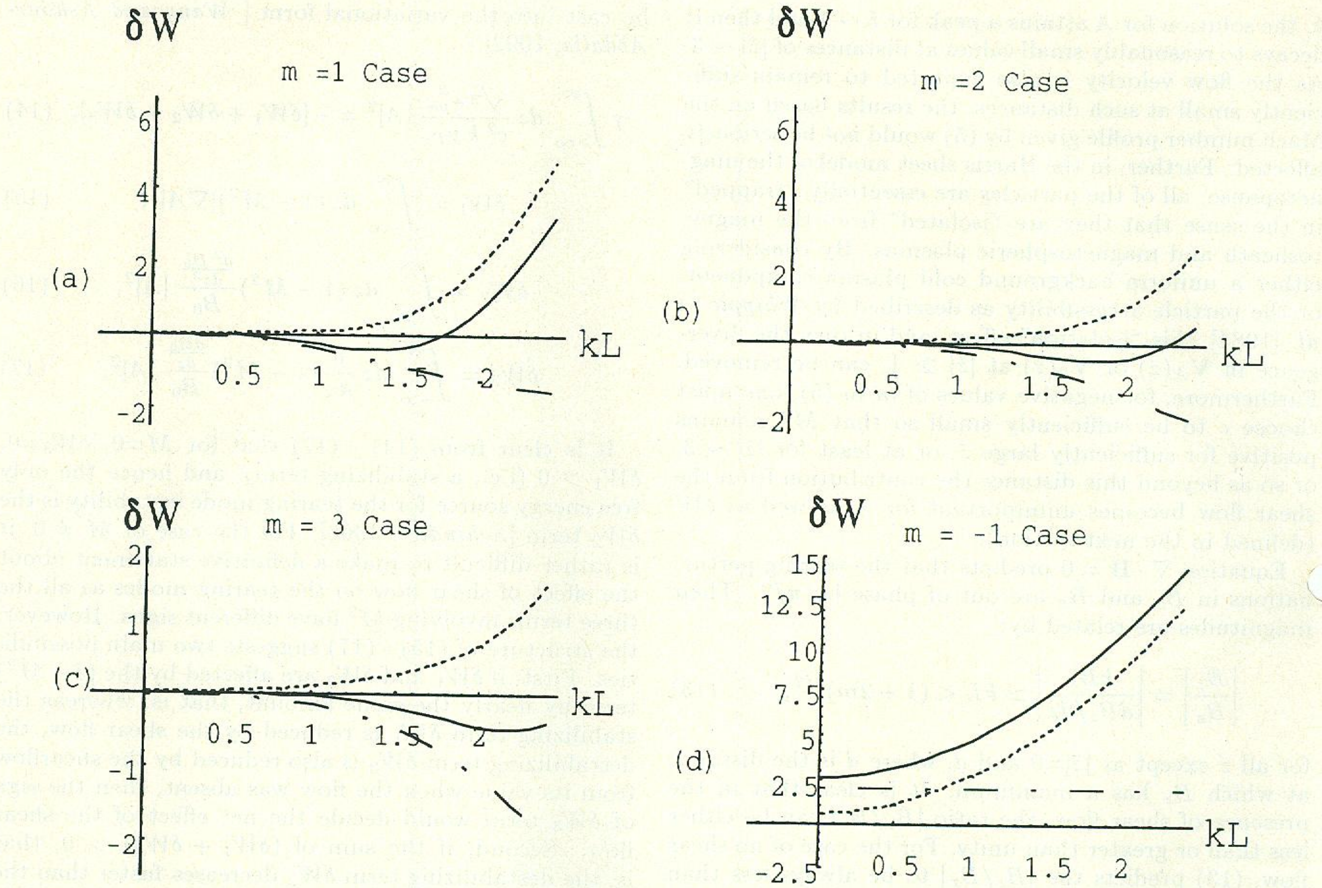

Figure 2. Variations of normalized $(\delta W_1 + \delta W_2)$ (dotted curves), δW_3 (dash-dot-dash curves), and $\delta W = (\delta W_1 + \delta W_2 + \delta W_3)$ (solid curves) versus normalized wavenumbers, $k\,L$. Figures 2a -2d correspond respectively to the case of shear flow index m = 1, 2, 3, and -1.

The Mach number profile given by (18) yields $\delta W_3 > 0$ as seen from (17). This leads to a stabilizing effect of the shear flow on the tearing modes as concluded by these authors. The above situation (i.e., $\delta W_3 > 0$) appears similar to the case m = -1 of Figure 2d for which δW_3 is also positive.

For the case considered here (i.e., the Mach number profile given by (5)), we see from Figures 2a-2c that the term $\delta W_3 < 0$ for m= 1, 2, and 3 (in general for any positive number), and the shear flow effects on the tearing modes are destabilizing [*Lakhina and Schindler*, 1983a; *Hoffmann*, 1975].

In general, we expect that the shear flow would have a destabilizing (stabilizing) effect on the tearing mode instability when the Mach number profiles has a minimum (maximum) at z=0 and it increases (decreases) away from the neutral axis.

We would like to point out that our analysis is strictly valid for the case where plasma and field distributions inside the singular layer are not significantly modified by the shear flow. Therefore the conclusions based on our model are expected to remain valid for the thin kinetic layers typical of the magnetopaue ($L < 10\rho_i$) [*Berchem and Russell*, 1982a]. In our analysis, the external region is modelled by incompressible MHD equations. This assumption can be justified because the field lines in this region remain frozen into the plasma as in the kink mode. The kinetic effects like Landau resonances are not expected to be important as both the electrons and the ions behave essentially as magnetized and their orbits are of "nonaxis-crossing" type. The cyclotron resonances would not be important as the modes have low frequencies. *Wang and Ashour-Abdalla* [1992] used the drift kinetic formalism for the external region. Although in their case the shear flow has a damping effect because $\delta W_3 > 0$ as discussed above, these authors did suggest the possibility of destabilization of the tearing modes for some other kinds of equilibria. *Kuznetsova et al.* [1994] used the kinetic formalism to investigate the case where the shear flow modifies the plasma and field structure in the singular layer. It is interesting to note that our equations for the external region, for example, (4), right hand side of (14), and (15) - (17), remain valid even for $B_y(\bar{z}) \neq 0$ provided that $k_y = 0$. However, the left hand side of (14) is modified, to the leading order, with the replacement of k by $k_{\parallel} = kL/L_s$, where $L_s = B_x'(0)/B_y(0)$ is the magnetic shear scale length. This effect would lead to the reduction of the growth rate γ [*Drake and Lee*, 1977; *Kuznetsova et al.*, 1994]. Hence except for the thick magnetopause conditions [*Berchem and Russell*, 1982b] where the shear flow can possibly affect L_s, our conclusions based on the simple model are expected to remain valid.

4. Conclusions

We have considered a rather idealized magnetopause equilibrium model with zero electric field and symmetrical plasma and field parameters on both sides of the current layer. Further, we considered the case where the presence of shear flow does not affect the assumed equilibrium. Therefore the model should apply to thin magnetopause layers.

We have argued, based upon our analytical dispersion relations (10)-(11) and the numerical results from the energy principle (14)-(17), that the tearing modes are destabilized (stabilized) when the Alfvén Mach number profile has a minimum (maximum) at the neutral axis (i.e., the axis where the magnetic field vanishes). This can explain naturally the seemingly conflicting results regarding the effects of shear flow on the tearing mode instability at the magnetopause.

Magnetic structures produced by tearing modes would be Doppler shifted because of plasma flows, and thus manifest as ULF turbulence with frequencies ~ 5 -650 mHz. The results are expected to be useful in identifying some of the ultralow-frequency modes observed at the magnetopause.

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