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A shear flow instability in plasma sheet region

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Abstract

A shear flow instability is studied in the plasma sheet region in three component cold plasma consisting of electrons, protons and oxygen ions. The linear dispersion relation is derived with velocity shear in each component, i.e. electrons, protons and oxygen ions. The dispersion relation is solved for the case of O^+ ion beam with shear flow passing through stationary electron–ion plasma. It is found that low-frequency waves could become unstable due to the velocity shear of the O^+ ion beam in the near earth plasma sheet region. The typical growth rate of the instability is found to be (0.2–0.5) mHz with parallel and perpendicular wavelengths ranging from (11–200)R_E and (13–32) km, respectively.

Keywords: Shear flow instability; Magnetic storms; Substorms; Plasma sheet; Low frequency waves

1. Introduction

Observations by several spacecraft suggest that heavy ions of ionospheric origin can sometimes dominate the composition of the outer magnetosphere and the plasma sheet region (Peterson et al., 1981; Sharp et al., 1981; Shelley et al., 1982; Hultqvist, 1991; Daglis et al., 1991, 1993; Daglis and Axford, 1996; Daglis, 1997; Cladis and Francis, 1992). Recent Geotail observations indicate the presence of tailward flowing energetic O^+ ion bursts in the distant magnetotail during the substorm expansion phase (Wilken et al., 1995; Nose et al., 2000). Energetic oxygen ions of ionospheric origin with hundreds of keV energies have also been observed in the cusp region by the POLAR satellite (Chen and Fritz, 2001). The presence of O^+ ions in the plasma sheet region may trigger several kind of plasma instabilities like, tearing instability (Schindler, 1974; Baker et al., 1982), fire-hose type instabilities (Davidson and Völk, 1968; Verheest and Lakhina, 1991; Hill and Voigt, 1992; Yoon et al., 1993; Lakhina, 1995, 1996), helicon mode instabilities (Lakhina and Tsurutani, 1997, 1998). Recently Singh et al. (2002) have shown that low-frequency quasi-electrostatic waves can be excited by the energetic O^+ ions in the ring current region.

Cladis and Francis (1992) estimated the magnetic and electric field changes in response to the O^+ ions pressure in the near earth magnetotail. Their estimation indicates that increased O^+ ions pressure in the near earth magnetotail could alter the electric and magnetic fields, leading to the development of shears in convection velocity near the flanks of the O^+ ions injection region. Recently, Lu Li et al. (2000) studied the velocity shear instability by considering the H^+ and O^+ ions to have the same flow velocity and the same velocity shear. They found that the growth rate of the shear flow instability increases with the oxygen ion flow shear.

In this paper, we study the linear instability of obliquely propagating low-frequency waves driven by velocity shear in a three components (H^+, O^+, e^-) cold, uniform magnetized plasma. A linear dispersion relation for such a system is derived in Section 2 by assuming the flow velocities and shear of H^+ and O^+ ions to be different. In Section 3, the linear dispersion relation is solved for nearly perpendicularly propagating waves with velocity shear in oxygen ions. For simplicity velocity shear for e^- and H^+ are not taken into account as we want to study the effect of O^+ ion shear on the growth of low-frequency waves. The results are concluded in the last section.

2. Theoretical analysis

We model the plasma sheet region by a three component plasma consisting of electron, proton and oxygen ions (e^-, H^+, O^+) embedded in a uniform magnetic field $\vec{B}_0$ directed

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along X-axis. We assume H^+ and O^+ ions to have different flow velocities and flow shear. The plasma response is governed by the following set of fluid equations

$$\frac{\partial n_\alpha}{\partial t} + \nabla(n_\alpha \vec{v}_a) = 0, \tag{1}$$

$$m_\alpha \frac{d\vec{v}_\alpha}{dt} = q_\alpha(\vec{E} + \vec{v}_\alpha \times \vec{B}) - \frac{1}{n_\alpha}\nabla p_\alpha \tag{2}$$

together with Maxwell's equation and quasi-neutrality condition

$$c^2 \nabla \times \vec{B} = \frac{1}{\varepsilon_0}\sum_\alpha q_\alpha n_\alpha \vec{v}_\alpha, \tag{3}$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}, \tag{4}$$

$$n_e = n_p + n_o, \tag{5}$$

where n_α, $\vec{v}_\alpha$, p_α and q_α, respectively, are the number density, velocity, pressure and charge of the plasma species $\alpha = e^-$, H^+ and O^+, $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field intensity.

We assume the equilibrium velocity to have the following profile:

$$\vec{V}_\alpha = v_\alpha^0(z)\hat{e}_x$$

The equilibrium would, then, demand that

$$\frac{d}{dz} p_\alpha^0 = 0,$$

i.e. $p_\alpha^0 = \text{constant}$.

The simplified equilibrium state considered here is expected to hold good in the region away from the neutral sheet where the magnetic field have large gradient.

After linearizing the set of Eqs. (1)–(5) and Fourier analyzing the perturbed quantities, which are assumed to vary as $e^{i(k_x x + k_y y - \omega t)}$ and considering the phase velocity to be greater than thermal velocity (i.e., cold plasma approximation), we get the following system of equations

$$\begin{bmatrix} \Pi_{11} & \Pi_{12} & \Pi_{13} \\ \Pi_{21} & \Pi_{22} & \Pi_{23} \\ \Pi_{31} & \Pi_{32} & \Pi_{33} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ iE_z \end{bmatrix} = 0. \tag{6}$$

The linear dispersion relation is obtained by equating the determinant equal to zero i.e.

$$\begin{vmatrix} \Pi_{11} & \Pi_{12} & \Pi_{13} \\ \Pi_{21} & \Pi_{22} & \Pi_{23} \\ \Pi_{31} & \Pi_{32} & \Pi_{33} \end{vmatrix} = 0, \tag{7}$$

where

$$\Pi_{11} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left\{\left(1 - \frac{\Omega_\alpha^2}{\omega_{\alpha c}^2}\right)\frac{\omega^2}{\Omega_\alpha^2} + \frac{\omega S_\alpha k_y V_{\alpha x}}{\Omega_\alpha^2 \omega_{\alpha c}} - \frac{k_y^2 V_{\alpha x}^2}{\omega_{\alpha c}^2}\right\} + k_y^2 c^2, \tag{8}$$

$$\Pi_{12} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left\{\frac{\omega S_\alpha}{\Omega_\alpha \omega_{\alpha c}} - \frac{\Omega_\alpha k_y V_{\alpha x}}{\omega_{\alpha c}^2}\right\} - k_x k_y c^2, \tag{9}$$

$$\Pi_{13} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left\{\frac{\omega S_\alpha}{\omega_{\alpha c}^2} + \frac{k_y V_{\alpha x}}{\omega_{\alpha c}}\right\}, \tag{10}$$

$$\Pi_{21} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left(\frac{\Omega_\alpha k_y V_{\alpha x}}{\omega_{\alpha c}^2}\right) + k_x k_y c^2, \tag{11}$$

$$\Pi_{22} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left(\frac{\Omega_\alpha^2}{\omega_{\alpha c}^2}\right) - k_x^2 c^2, \tag{12}$$

$$\Pi_{23} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left(\frac{\Omega_\alpha}{\omega_{\alpha c}}\right), \tag{13}$$

$$\Pi_{31} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left(\frac{k_y V_{\alpha x}}{\omega_{\alpha c}}\right), \tag{14}$$

$$\Pi_{32} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left(\frac{\Omega_\alpha}{\omega_{\alpha c}}\right), \tag{15}$$

$$\Pi_{33} = \sum_\alpha \frac{\omega_{p\alpha}^2}{\theta_\alpha}\left(\frac{\Omega_\alpha^2}{\omega_{\alpha c}^2}\right) - k^2 c^2, \tag{16}$$

where

$$\theta_\alpha = 1 - \frac{\Omega_\alpha^2}{\omega_{\alpha c}^2},$$

And where $\Omega_\alpha = \omega - \vec{k}\vec{V}_\alpha$, $S_\alpha = \partial V_\alpha/\partial z$, $\omega_{p\alpha} = \sqrt{q_\alpha^2 n_\alpha/\varepsilon_0 m_\alpha}$, $\omega_{\alpha c} = q_\alpha B_0/m_\alpha$, respectively are the Doppler shifted frequency, velocity shear, plasma frequency, gyro frequency of species α and $k = \sqrt{k_x^2 + k_y^2}$ is wave number. For the case of parallel propagation and uniform velocity, i.e. $k_y = 0$, $S_\alpha = 0$, the $\Pi_{12} = \Pi_{21} = \Pi_{13} = \Pi_{31} = 0$, and dispersion relation (7) becomes identical to that derived by Verheest (2000) and yields transverse, electromagnetic right- and left-hand circularly polarized modes.

3. Analysis of the dispersion relation

The general dispersion relation equation (7) is very complicated to be solved analytically. To simplify Eq. (7), we assume the electrons and ions to have zero shear velocity, whereas the oxygen ion have a shear flow velocity $V_0(z)$ with velocity shear $S = \partial V_o/\partial z$. Further, we assume the low-frequency waves ($\Omega_o/\omega_{oc} \ll 1$) propagates obliquely to ambient magnetic field with $V_o/V_{Ao} \ll 1$. In the limit of above approximations the general dispersion relation (7) reduces to

$$\Pi_{33}[\Pi_{11}\Pi_{22} - \Pi_{12}\Pi_{21}] = 0 \tag{17}$$

which gives two modes $\Pi_{33} = 0$ or $[\Pi_{11}\Pi_{22} - \Pi_{12}\Pi_{21}] = 0$.

From $\Pi_{33} = 0$, we get

$$\omega^2 = k^2 V_A^2, \tag{18}$$

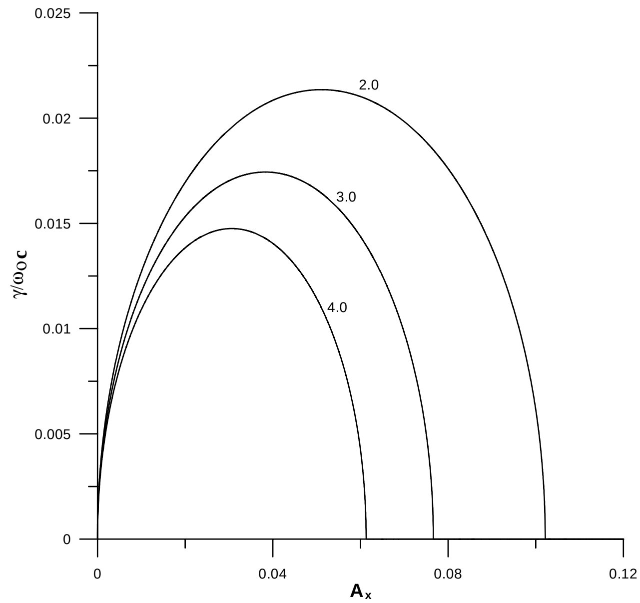

Fig. 1. Variation of normalized growth rate γ/ω_{oc} versus normalized wave number A_x for the shear flow instability driven by O^+ ions in the plasma sheet region, for the following parameters: $S=15.0$, $A_y=600$, $\varepsilon=2.0$, 3.0, 4.0.

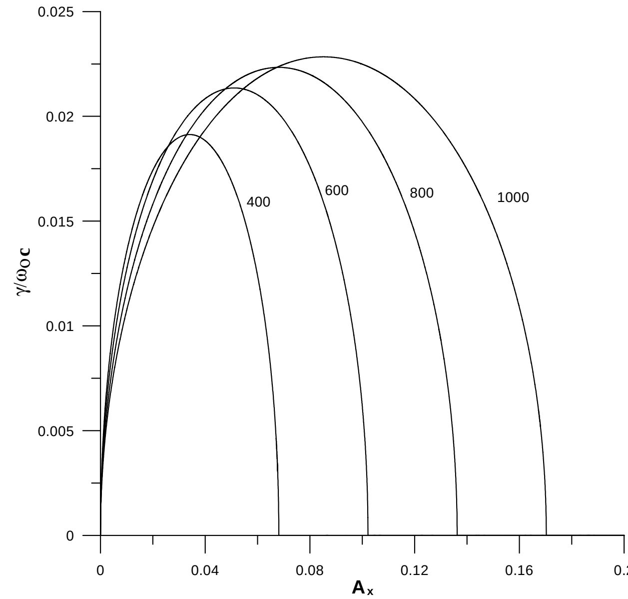

Fig. 2. Variation of normalized growth rate γ/ω_{oc} versus normalized wave number A_x for the shear flow instability driven by O^+ ions in the plasma sheet region, for the following parameters: $S=15.0$, $\varepsilon=2.0$, $A_y=400$, 600, 800, 1000.

where

$$V_A=\frac{B_0}{\sqrt{\mu_0(m_i n_i^0+m_0 n_o^0)}}$$

which is fast Alfvén mode.

From $[\Pi_{11}\Pi_{22}-\Pi_{12}\Pi_{21}]=0$, we get the slow Alfvén mode, which gives

$$\omega^2=\frac{M_2A_x^2+SA_xA_y}{M_1(M_2+A_y^2)}\,\omega_{oc}^2 \qquad (19)$$

For $S<0$, gives the condition for shear flow instability

$$|S|>M_2\frac{k_x}{k_y} \qquad (20)$$

where, $M_1=(1+(m_p n_p^0/m_o n_o^0))$, $M_2=(1+(n_p^0/n_o^0))m_o/m_e$, $A_x=k_xV_{Ao}/\omega_{oc}$, $A_y=k_yV_{Ao}/\omega_{oc}$, $S=S_o/\omega_{oc}$, and, $V_{Ao}=B_0/\sqrt{\mu_0 m_o n_o^0}$, is the Alfvén speed corresponding to O^+ ions. In Eqs. (18)–(20) we have neglected the terms of the order of $(m_e/m_{p,o})$.

From above Eq. (19) it is clear that for $S=0$, we recover the dispersion relation for the obliquely propagating shear Alfvén wave (Hasegawa and Uberoi, 1982). These modes are stable, which is expected as there is no free energy source to drive the instability. These obliquely propagating shear Alfvén waves become unstable for a finite negative velocity shear as seen from Eq. (19).

We have numerically computed the growth rate from Eq. (19) for the shear flow instability in the presence of O^+ ion in the plasma sheet region. Fig. 1 shows the variation of normalized growth rate (γ/ω_{oc}) with normalized wave number A_x for $S=15.0$ and $A_y=600.0$ for different values of $\varepsilon=(n_p^0/n_o^0)=2.0, 3.0, 4.0$. It is found that the normalized growth rate of the shear flow instability increases with the increase of O^+ ion concentration. The average O^+ ions number density in plasma sheet region is about 0.2 cm^{-3} during highly disturbed time (Lennartsson and Shelley, 1986) and in the inner plasma sheet, $n_i \sim 0.5$ cm^{-3}, therefore the parameter $\varepsilon=(n_p^0/n_o^0)$ could have maximum value up to 2.5. Some studies indicate values of 0.5–100 for the (n_p^0/n_o^0) density ratio in the outer magnetosphere depending on the magnetic activity level (Lennartsson and Sharp, 1982). Fig. 2 shows the variation of normalized growth rate with A_x for $S=5.0$, $\varepsilon=2.0$ for various values of A_y as indicated on the curves. From Fig. 2 one can see that the normalized growth rate increases with the increase of A_y. In Fig. 3, we plot normalized growth rate as a function of normalized wave number A_x for different values of velocity shear $S=5.0$, 8.0, 12.0, 15.0. One can see from Fig. 3, that normalized growth rate increases with the increase of O^+ ion shear.

4. Conclusion

Peterson et al. (1981) have reported $V_p \sim 31$ km s^{-1} and $V_o \sim 43 \pm 60$ km s^{-1} with large uncertainties. Candidi et al. (1982) and Orsini et al. (1985) have reported the flow velocity of O^+ ions as varying between ~ 20 and 120 km s^{-1} in the plasma sheet. Stokholm et al. (1985) have observed cold anisotropic O^+ ion beam, in the plasma sheet region with velocities ranging between $V_o \sim 20$ and 60 km s^{-1}. However, in the absence of simultaneous measurement of V_p, it is rather difficult to find the relative drift speed between O^+ and H^+ ion in the plasma sheet region.

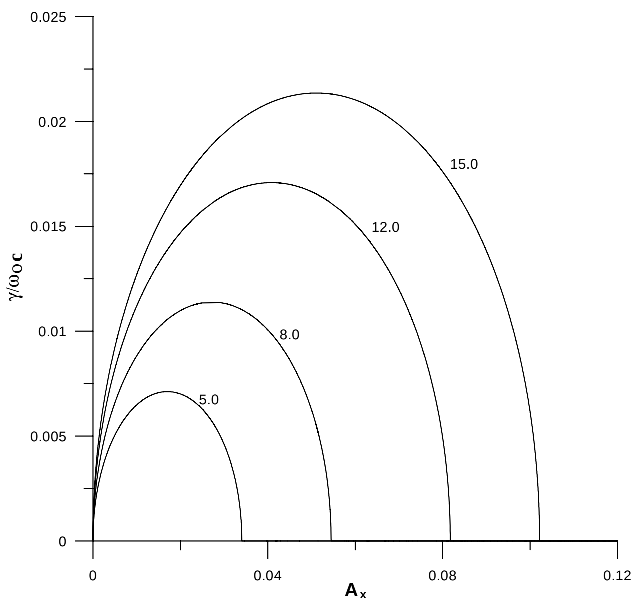

Fig. 3. Variation of normalized growth rate γ/ω_{oc} versus normalized wave number A_x for the shear flow instability driven by O^+ ions in the plasma sheet region, for the following parameters: $A_y = 600$, $\varepsilon = 2.0$, $S = 5$, 8, 12, 15.

So far there are no specific measurements for velocity gradients in plasma sheet region. However satellite observations have established the existence of the plasma sheet boundary layer, which supports intense ion flows, field aligned currents, and an intense broadband electrostatic noise (BEN) (Parks et al., 1984). These observations suggest that the intense ion flows are concentrated in a thin boundary layer. Therefore sufficiently large velocity shear is expected to be present in the region of the plasma sheet boundary layer. Also the estimation of magnetic and electric field changes in response to the O^+ ions pressure in the tail suggested the development of large shear near the flanks of the O^+ ions injection region (Cladis and Francis, 1992).

Based on observations, we consider the following parameters for the plasma sheet region: $n_p = 0.5\ \mathrm{cm}^{-3}$ and $n_o = 0.2\ \mathrm{cm}^{-3}$ (Lennartsson and Shelley, 1986) and $V_o = 40\ \mathrm{km\ s}^{-1}$ (Stokholm et al., 1985). Then for $B_0 = 25$ nT, we get $\omega_{oc} = 2.4 \times 10^{-2}$ Hz, $V_{Ao} = 300\ \mathrm{km\ s}^{-1}$. For $S = (5.0\text{–}15.0)$, $A_y = (400\text{–}1000)$, $A_x = (0.01\text{–}0.17)$ from Figs. 1–3, we get the range of growth rates, parallel and perpendicular wavelengths respectively, as $\gamma/2\pi = (0.2\text{–}0.5)$ mHz, $\lambda_\parallel = 2\pi/k_x = (11\text{–}200) R_E$, and $\lambda_\perp = 2\pi/k_y = (12\text{–}32)$ km. The range of shear flow scale length corresponding to $S = (5\text{–}15)$ comes out to be (18–54) km which is larger than the perpendicular wavelength of the modes. This satisfies use of the local approximations.

It is well known that ionospheric O^+ ion feeding of the inner plasma sheet during the substorm can be efficient (Daglis and Axford, 1996). Our analysis shows that the velocity shear of ionospheric O^+ ions in the plasma sheet can excite low-frequency waves.

The growth time of the shear flow instability is calculated to be (32–60) min. The shear flow instability may trigger substorm only for the large O^+ ion velocity shear and for small O^+ ion shear where the growth rates are small, this instability may be active during geomagnetic storm.

The shear flow instability studied here may be responsible for the low-frequency turbulence (∼ few mHz–10 Hz) observed in the outer central plasma sheet region and plasma sheet boundary layer (Russell, 1972; Tsurutani et al., 1985; Bauer et al., 1995). Furthermore, the low-frequency turbulence excited by velocity shear can scatter the electrons trapped in the central plasma sheet region and thus could facilitate the excitation of tearing mode leading to the substorm onset.

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