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Helicon modes driven by ionospheric O^+ ions in the plasma sheet region

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Abstract. The presence of ionospheric-origin oxygen ions in the plasma sheet region results in only partial cancellation of the electron Hall current leading to the occurrence of the helicon mode rather than the Alfvén mode. It is shown that the presence of ionospheric-origin oxygen ion beams with anisotropic pressure can excite helicon mode instability in the near-Earth plasma sheet region provided their Alfvénic Mach numbers lie in a certain range. The helicon modes are easily excited under the conditions when the usual long wavelengths fire-hose modes are stable. The typical real frequencies of the excited helicon modes are between 1 to 10 mHz, and the typical e-folding time of the instability is about 3 to 15 minutes at wavelengths of 1 to 5 R_E. Therefore these modes are likely to attain saturation during enhanced convection events lasting for a few hours. Large amplitude helicon modes would distort the ambient magnetic field and may be observable as flux ropes. Low-frequency turbulence produced by these modes could scatter electrons and help excitation of the ion tearing modes leading to substorm onset.

1. Introduction

Recent observations suggest that ionospheric-origin O^+ ions consititute an important and some times dominant part of the outer magnetosphere and the near-Earth plasma sheet region [*Lennartsson*, 1994]. Observations by GEOTAIL indicate the presence of tailward flowing energetic O^+ ion bursts in the distant magnetotail [*Wilken et al.*, 1995]. Two most important ionospheric outflow regions for the O^+ ions are the auroral region and the dayside cleft [*Lockwood et al.*, 1985]. Recently, it has been shown that the auroral ionospheric ion feeding of the inner plasma sheet during substorms can be fast (i.e., $\sim$ characteristic substorm timescales), and that the ionosphere could actively influence the substorm energization processes by responding to the increased solar wind-magnetosphere coupling [*Daglis and Axford*, 1996].

It has been suggested that enhanced densities of ionospheric O^+ ions in some localized region in the plasma sheet would favor the excitation of the ion tearing instability [*Schindler*, 1974; *Baker et al.*, 1982], velocity shear instabilities [*Cladis and Francis*, 1992], or fire-hose type instabilities [*Davidson and Völk*, 1968; *Verheest and Lakhina*, 1991; *Yoon et al.*, 1993; *Lakhina*, 1995, 1996], which could lead to the onset of the substorms. Thus, it is important to undersand the role of ionospheric O^+ ions on the stability and dynamics of the near-Earth plasma sheet which ultimately controls the substorm processes.

In this paper we show that the presence of anisotropic ionospheric-origin O^+ ion beams can excite the helicon mode in the near-Earth ($X \approx$ -10 R_E to -15 R_E) plasma sheet region. In an electron-proton plasma, the dispersion relation for the right-hand polarized low-frequency modes, i.e., $\omega \ll \Omega_p$ (here ω and Ω_p represent the wave and the proton cyclotron frequencies, respectively), propagating parallel to the magnetic field, $\mathbf{B}_0$, gives the MHD Alfvén modes. In this case the proton Hall current completely cancels the electron Hall current, and the wave is maintained by the proton polarization current [*Papadopoulos et al*, 1994]. However, in the presence of oxygen ions, the ion (both proton and oxygen) Hall currents cannot completely cancel the electron Hall current unless $\omega \ll \Omega_o$ (Ω_o being the oxygen ion cyclotron frequency). Therefore for the case when O^+ ions are weakly magnetized or unmagnetized, they carry negligible Hall current, and the resultant ion Hall current is not sufficient to neutralize the electron Hall current. This situation could give rise to helicon waves [*Papadopoulos et al.*, 1994; *Zhou et al.*, 1996]. It has been suggested that helicon waves could lead to the fast current and flux penetration across the plasma sheet [*Papadopoulos et al.*, 1994], thus affecting the substorm dynamics. We shall show, for the first time, the possibility of driving the helicon mode instability in the magnetotail by the ionospheric-origin oxygen ion beams.

2. Helicon Mode Instability

The dispersion relation for the electromagnetic modes propagating parallel to the magnetic field, $\mathbf{B_0} = B_0\mathbf{x}$ in a multispecies plasma can be written [*Lakhina*, 1995], in standard notation,

$$\omega^2 = c^2k^2 - \sum_j \omega_{pj}^2 \left[\frac{\omega - kU_j}{k\alpha_{\parallel j}} Z(\eta_j) + (\frac{\alpha_{\perp j}^2}{\alpha_{\parallel j}^2} - 1)\{1 + \eta_j Z(\eta_j)\}\right], \qquad (1)$$

where $\omega_{pj} = (4\pi q^2 N_j/m_j)^{1/2}$ and $\Omega_j = q_j B_0/m_j c$ are the plasma and the gyrofrequency of the jth species,

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with $j = e$, p and o for electrons, protons and the oxygen ions respectively, U_j is the drift velocity of the jth species, and $\alpha_{\perp j}$ and $\alpha_{\| j}$ are respectively the perpendicular and parallel thermal velocities with respect to $\mathbf{B_0}$, and $Z(\eta_j)$ is the well known plasma dispersion function with the argument $\eta_j = (\omega - kU_j \pm \Omega_j)/k\alpha_{\| j}$. The $\pm$ sign in η_j denotes the RH (+ sign) and the LH (− sign) modes.

We consider the case of $\eta_j \gg 1$ for each species, $(\omega - kU_j)^2 \ll \Omega_j^2$ for $j = e$ (electrons) and p (protons), and $\omega^2 \ll c^2k^2$ and take $U_p = 0$ (i.e., proton rest frame), then (1) can be written as

$$\omega^2 \pm \frac{N_o m_e}{N_p m_p}\Omega_e \omega - k^2 V_{Ap}^2 (1 - \frac{A_e}{2} - \frac{A_p}{2}) - \frac{N_o}{N_p}\frac{\Omega_p \Omega_o (\omega - kU_o)}{\omega - kU_o \pm \Omega_o} + \frac{A_o k^2 V_{Ap}^2 \Omega_o^2}{2(\omega - kU_o \pm \Omega_o)^2} = 0. \quad (2)$$

Here pressure anisotropy of the plasma species is represented by $A_j = (\beta_{\| j} - \beta_{\perp j})$, where $\beta_{\| j}$ and $\beta_{\perp j}$ are respectively the parallel and the perpendicular plasma beta for the jth species, and $V_{Ap} = B_0/(4\pi\rho_p)^{1/2}$ is the Alfvén speed with respect to the proton mass density $\rho_p = N_p m_p$.

Neglecting the oxygen ion dynamics in (2), and considering $\omega^2 \ll \frac{N_o m_e}{N_p m_p}\Omega_e \omega$, we get the helicon mode in multi-ion plasma,

$$\omega_0 = \pm \frac{N_p}{N_o}(1 - \frac{A_e}{2} - \frac{A_p}{2})\frac{k^2c^2}{\omega_{pe}^2}\Omega_e, \quad (3)$$

which is very similar in structure to the dispersion relation for the usual helicon mode, $\omega_H = \frac{k^2c^2}{\omega_{pe}^2}\Omega_e$, in electron -proton plasma. Equation (3) shows that electron dynamics dominates the interaction between the electromagnetic waves and the multi-ion plasma, thus, there is a possibility of field aligned current carried by the helicons in the multi-ion plasma [*Papadopoulos et al.*, 1994; *Zhou et al.*, 1996].

Now, we shall take into account the dynamics of the O^+ ions, and look for an instability near the helicon mode frequency ω_0. Once again considering $\omega^2 \ll \frac{N_o}{N_p}\Omega_p \omega$, and writing $\omega = \omega_0 + \delta$, (2) simplifies to

$$\delta^3 + [2(\omega_0 - kU_o) \pm \Omega_o]\,\delta^2 + (\omega_0 - kU_o)^2\,\delta \mp \left[-\frac{A_o k^2 V_{Ap}^2}{2R} + (\omega_0 - kU_o)(\omega_0 - kU_o \pm \Omega_o)\right]\Omega_o = 0, \quad (4)$$

where $R = (N_o m_o / N_p m_p)$ represents the relative oxygen ion mass density with respect to protons.

For the special case of isotropic plasma system,i.e., $A_e = A_p = A_o = 0$, (5) becomes a quadratic equation, and the helicon mode instability with RH polarization is excited by the O^+ ion beam provided

$$\frac{kV_{Ap}}{R\Omega_o} < M < \left[\frac{kV_{Ap}}{R\Omega_o} + \frac{4\Omega_o}{kV_{Ap}}\right], \quad (5)$$

where $M = U_o/V_{Ap}$ is the oxygen ion Alfvén Mach number where V_{Ap} is the Alfvén speed calculated using the proton mass density.

We solved (5) using *Mathematica* for both RH and LH polarized modes. We find that the helicon mode instability occurred for the RH mode only. Therefore results for the real frequency, $\omega_r = (\omega_0 + Re\delta)$ and growth rate, $\gamma = Im\delta > 0$ for RH modes are shown in Figures 1–2 for the parameters relevant to the central plasmasheet (CPS) region where we have taken $\beta_{\| o} = 3.5$.

Figures 1a and 1b show that ranges of real frequencies and growth rate increase when A_o is increased. In Figure 1, growth rates could attain the maximum value for a certain value of the normalized wavenumber. But, in Figures 2a and 2b, we have to truncate the curves for real frequency and the growth rates before the latter could attain the maximum value, say γ_{max}/Ω_o. The truncation was necessary as the assumption of treating the oxygen ions as cold, i.e., $\eta_0^2 \gg 1$, breaks down for values of the wavenumber kV_{Ap}/Ω_o larger than those shown in Figures 2a and 2b.

Figures 2a and 2b show that an increase of M and R has destabilizing effects on the helicon mode. The range of excited real frequencies, growth rates, and of

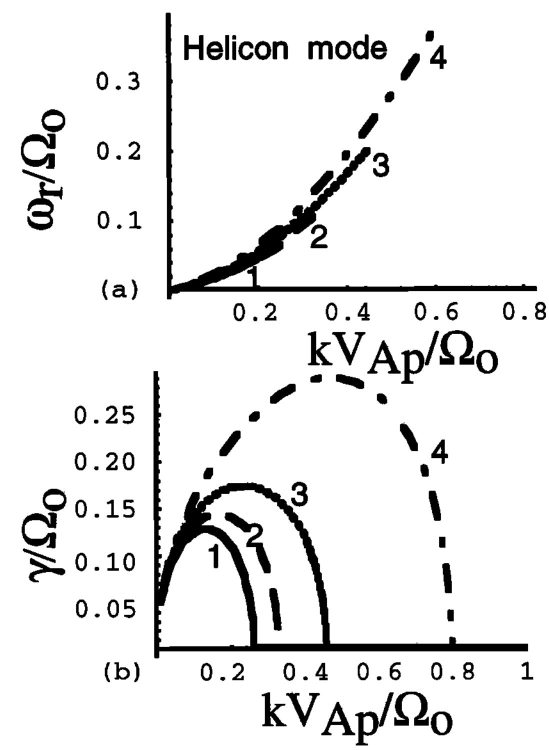

Figure 1. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the helicon mode instability driven by O^+ ions in the CPS region for $M = U_o/V_{Ap} = 0.25$, $R = \rho_o/\rho_p = 1.0$, $A_e = A_p = 0$, and $\beta_{\| o} = 3.5$. The curves 1, 2, 3, and 4 are respectively for $A_o = (\beta_{\| o} - \beta_{\perp o}) = 0.1, 0.5, 1.0$, and 2.0. For the parameters considered here as well as in Figures 2 and 3, the LH mode instability does not exist.

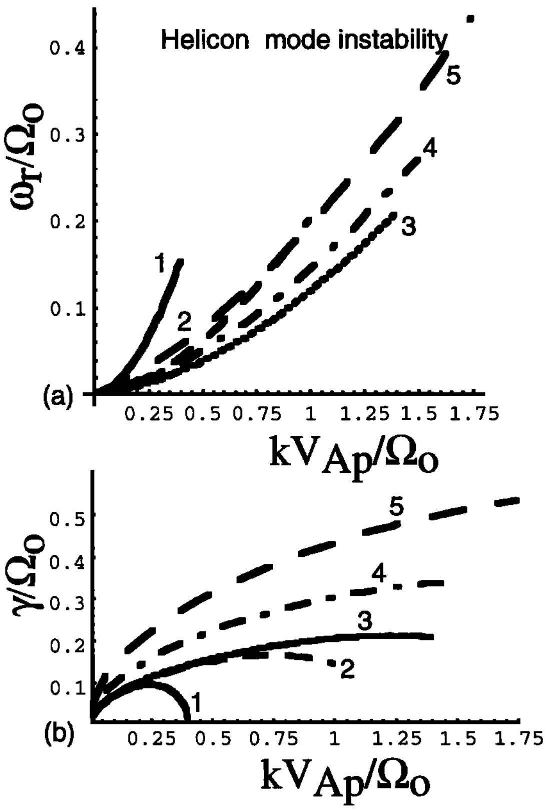

Figure 2. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the helicon mode instability driven by O^+ ions in the CPS region for $A_e = A_p$=0, and A_o = 2.0. For the curves 1, 2, and 3, M=0.05, and R= 1.0, 5.0, and 10.0 respectively. For the curves 4 and 5, R= 10.0 and M= 0.1, and 0.2 respectively.

unstable ks are increased significantly by an increase in R from 1 to 10 (cf. curves 1, 2 and 3), and of M from 0.1 to 0.25 (cf. curves 3, 4 and 5). Further, the positive (negative) values of proton anisotropy, A_p, lead to increased (decreased) values for real frequencies as well as growth rates (not shown). The effects due to electron ansiotropy, A_e, were not found to be significant (not shown).

We may point out that the helicon mode instability is excited at much lower (than the proton cyclotron) frequencies and at much longer wavelengths than the right hand beam resonant instability (typically slightly less than the proton cyclotron frequencies) [*Gary et al.*, 1985; *Tsurutani et al.*, 1985]. An important feature of the helicon mode instability is that it is excited at smaller Mach numbers (typically $M_o \sim 0.05 - 0.25$ or so) than that required by resonant beam instability (typical $M \geq 1$). We would like to point out the similarities and differenes between the helicon modes and the finite gyroradius fire-hose modes studied by *Davidson and Völk* [1968] and *Yoon et al.* [1993]. Both the modes have finite real frequencies and both are destabilized by the pressure anisotropy having $\beta_\|$ greater than $\beta_\perp$. In the fire-hose mode studied by *Davidson and Völk* [1968] and *Yoon et al.* [1993], the real frequency of the mode arises due to finite Larmor radius effects, the mode becomes purely growing when the finite Larmor radius effects are neglected. In our case the real frequency of the helicon modes arises due to partial cancellation of the electron Hall current in the presence of unmagnetized or partially magnetized O^+ ions and not due to the finite Larmor radius effects which are neglected. The probable cause of the similarity of both modes is the breaking of MHD constrain, i.e., the non-idealness. Since the coefficients of the dispersion relations in the above quoted works are different in structure, a complete analysis including both the oxygen ion and the finite Larmor radius effects is required to make sure whether the helicon mode and the modes discussed by *Davidson and Völk* [1968] and *Yoon et al.* [1993] are the same or different. This is beyond the scope of this paper. Further, the works of *Davidson and Völk* [1968] and *Yoon et al.* [1993] have no minor ion species such as O^+ ions as we do. In addition we consider the effect of O^+ streaming relative to the background plasma, and find that the parallel Mach number, M, of the oxygen ions gives rise to the larger effective $\beta_{\|o}$ thus, leading to destabilization of the mode below the classical fire-hose instability limit.

3. Discussion and Summary

Based on observations and theoretical models, we consider the following parameters for the the central plasma sheet in the region $X \sim$ -10 R_E to -15 R_E: A_0 =0.1 to 2.0 [*Daglis et al.*, 1991; *Lennartsson*, 1994; *Cladis and Francis*, 1992], R = 1 - 10 [*Wilken et al.*, 1995], and $|U_o - U_p| \approx 10 - 60$ km s^{-1} [*Peterson et al.*, 1981; *Orsini et al.*, 1985]. Then, for B_0 = 10 nT and N_p = 0.5 cm^{-3}, we get typical Mach numbers M = 0.025 - 0.25 in the CPS region.

Figures 1 -2 show that the range of excited real frequencies, growth rates, and unstable wavelengths, $\lambda = 2\pi/k$, are respectively ω_r = (0.1 - 0.5) Ω_o =(1.0 - 5.0) mHz, γ = (0.1–0.5) Ω_o=(1.0 - 5.0) mHz, and $\lambda = V_{Ap}/(0.1 - 1.75)\Omega_o$ = (1 - 15) R_E for M = (0.01 - 0.25), R = 1 - 10, A_o = 0.1 - 2.0, B_0 = 10 nT and N_p = 0.5 cm^{-3}. Hence the instability would preferentially excite low-frequency waves with wavelenghts $\sim$ (0.8 - 15) R_E in the CPS. The typical e-folding time of the instability is about 3 to 15 minutes at wavelengths of $\lambda \approx$ 1 to 5 R_E, which is reasonably short. Therefore, these modes could attain saturation as the enhanced convection events may last for a few hours.

The existence of large amplitude helicon modes driven by the free energy of the ionospheric-origin O^+ ion beams in the CPS region may CPS have some interesting consequences for the substorm processes. Firstly the large scale fluctuating z and y components, i.e., δB_z and δB_y, associated with the helicon modes could twist the equilibrium magnetic field into flux ropes. This gives an indication that the helicon modes may be playing some role in the processes related to oxygen ion bursts associated with multiple flux ropes in the distant magnetotail as observed by GEOTAIL [*Wilken et al.*, 1995]. Secondly, the large amplitude δB_z could produce localised minima in the z component of the 2D equilibrium magnetotail magnetic field near the neutral axis. Moreover, the low-frequency turbulence due to the helicon modes could scatter electrons trapped in the CPS region. Both these factors would make these localized minima (separated by the wavelength of the excited modes) to be the potential site for the excitation of the tearing mode instabilities which could lead to the onset of the expansion phase of the substorm. Thirdly, the helicon mode may be responsible for some of the low-frequency RH polarized electromagnetic noise in the ULF - ELF frequency range observed in the CPS and plasma sheet boundary layer [*Russell*, 1992; *Tsurutani et al.*, 1985, 1987; *Bauer et al.*, 1995].

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