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Role of helicon modes in the injection of oxygen ions in the ring current

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Abstract

The presence of an ionospheric-origin anisotropic oxygen ion beam can excite a helicon mode instability in the near-Earth plasma sheet region. The helicon modes can be easily excited under the conditions when the usual long wavelength fire-hose modes are stable. The helicon modes are likely to attain saturation as the typical e-folding time of the instability is about a few minutes in the near-Earth plasma sheet region. Therefore, the instability could significantly affect substorm dynamics and lead to enhanced ionosphere–magnetosphere coupling. Low-frequency turbulence produced by these modes could scatter electrons trapped in the inner central plasma sheer region and help excite the ion tearing modes, leading to substorm onset. As a result, the oxygen ions would be injected into the Earth's nightside magnetosphere. Repeated injections by this process would lead to enhanced oxygen ion fluxes in the storm-time ring current. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Helicon modes; Oxygen; Ring current

1. Introduction

Recent observations suggest that ionospheric-origin O^+ ions constitute an important part of the ring current and the near-Earth plasma sheet region during storms substorms (Peterson et al., 1981; Sharp et al., 1981; Shelley et al., 1982; Lennartsson and Shelley, 1986; Gloeckler and Hamilton, 1987; Hamilton et al., 1988; Hultqvist, 1991; Daglis et al., 1991, 1993, 1994a,b, 1998; Lennartsson, 1994). Wilken et al. (1995) and Zong et al. (1997) have reported substorm-associated tailward flowing energetic O^+ ion bursts in the distant magnetotail. The dominant mechanisms for the injection of ionospheric O^+ into the magnetosphere, and their subsequent acceleration to ring current energies during a storm are yet to be fully understood (Daglis et al., 1999; Hultqvist et al., 1999).

The auroral region and the dayside cleft are considered to be the two most important ionospheric outflow regions for the O^+ ions (Lockwood et al., 1985; Yau et al., 1986; Delcourt et al., 1989; Cladis and Francis, 1992). Oxygen ions extracted from the ionosphere, either from the cusp or auroral region, first travel along the lobe field lines close to the plasma sheet or in the plasma sheet boundary layer, until their encounter with the neutral sheet where they are accelerated to higher energies up to several tens of keV (Sharp et al., 1981; Candidi et al., 1982; Möbius et al., 1987; Cladis and Francis, 1992). Direct injection of ionospheric ions from auroral ionosphere into the near-Earth magnetotail has been suggested by Daglis et al. (1994a). The ionospheric ions are accelerated initially to about 40 keV while flowing out of the auroral ionosphere (Lundin and Hultqvist, 1989) and subsequently to energies of 80 keV or more (Daglis et al., 1994b; Wodnicka and Banaszkiewicz, 1997) while being injected into the near-Earth magnetotail. During the direct injection process, the outflowing ionospheric ions move along auroral field lines mapping equatorially to the inner plasma sheet. Daglis and Axford (1996) have shown that auroral ionospheric ion feeding of the inner plasma sheet

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during substorms can be fast (i.e., ~ characteristic substorm time scales). This suggests that the ionosphere could actively influence the substorm energization processes by responding to the increased solar wind–magnetosphere coupling.

It is interesting to note that ionospheric O^+ ion fluxes are observed to increase dramatically in the near-Earth ($X \sim -6$ to $-15\ R_E$) plasma sheet region (Daglis et al., 1990, 1991; Kistler et al., 1992). This region is Earthward of the general vicinity where the near-Earth neutral line is expected to form during the growth phase of substorms (Nagai et al., 1998). It has been suggested that enhanced densities of ionospheric O^+ ions in some localized region in the plasma sheet could excite several plasma instabilities, such as, ion tearing instability (Schindler, 1974; Baker et al., 1982), velocity shear instabilities (Cladis and Francis, 1992), firehose-type instabilities (Davidson and Völk, 1968; Verheest and Lakhina, 1991; Hill and Voigt, 1992; Yoon et al., 1993; Lakhina, 1995, 1996) and helicon mode instability (Lakhina and Tsurutani, 1997, 1998) which could lead to the onset of the substorms. Thus, the increased fluxes of ionospheric O^+ ions are expected to significantly affect the stability and dynamics of the near-Earth plasma sheet which ultimately controls the substorm processes.

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; Lakhina and Tsurutani, 1997, 1998). The helicon waves could lead to the fast current and flux penetration across the plasma sheet (Papadopoulos et al., 1994), thus affecting substorm dynamics. Lakhina and Tsurutani (1997, 1998) studied the helicon instability in the magnetotail driven by cold O^+ ion beams. Here, we shall discuss the excitation of the helicon mode instability by hot O^+ 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; Lakhina and Tsurutani, 1997), in standard notation,

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

where $\omega_{pj} = (4\pi q^2 N_j/m_j)^{1/2}$ and $\Omega_j = q_j B_0/m_j c$ are, respectively, the plasma and the gyrofrequency of the jth species, 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 $\alpha_{\parallel j}$ 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 $\eta_j = (\omega - kU_j \pm \Omega_j)/k\alpha_{\parallel j}$. The $\pm$ sign in η_j denotes the RH (+ sign) and the LH (− sign) modes. In writing (1), we have taken the distribution functions as drifted bi-Maxwellians. In the equilibrium state, the charge neutrally is maintained by taking $N_e = N_p + N_o$, where N is the density.

We shall solve (1) in the proton rest frame, i.e., $U_p = 0$, and will consider two special cases, namely, (1) non-neutral ionospheric oxygen ion beam passing through the plasma sheet region (corresponding to a finite field-aligned current in the equilibrium state), and (2) a neutralized oxygen ion beam (i.e., the current neutrality is maintained in the equilibrium state).

2.1. Non-neutral O^+ ion beam

The cast of ionospheric O^+ ion beam passing through the stationary ($U_p = 0$, and $U_e = 0$) plasma sheet region corresponds to the situation of a finite field-aligned current in the system. We treat the background plasma as cold, i.e., $\eta_e \gg 1$ and $\eta_p \gg 1$, and the O^+ ion beam as hot, i.e., $\eta_o < 1$. Further, considering $(\omega - kU_j)^2 \ll \Omega_j^2$ for $j = $ e (electrons) and p (protons), and $\omega^2 \ll c^2k^2$, (1) can be reduced to the following form:

$$k^2 V_{A_p}^2 \left(1 - \frac{A_e}{2} - \frac{A_p}{2}\right) - R\Omega_o^2 \left[-\frac{A_o}{\beta_{\parallel o}} + \frac{2\Omega_o(\Omega_o \mp kU_o)}{k^2\alpha_{\parallel o}^2} \right] \mp R\Omega_o\omega \left(1 + \frac{2\Omega_o^2}{k^2\alpha_{\parallel o}^2}\right) - \omega^2 - i\sqrt{\pi} R\Omega_o^2 \exp(-\eta_o^2) \times \left[\frac{\beta_{\perp o}}{\beta_{\parallel o}} \frac{(\omega - kU_o)}{k\alpha_{\parallel o}} \mp \frac{A_o}{\beta_{\parallel o}} \frac{\Omega_o}{k\alpha_{\parallel o}} \right] = 0. \tag{2}$$

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

On considering $\omega^2 \ll R\Omega_o\omega$, and writing $\omega = \omega_r + i\gamma$, where $\gamma^2 \ll \omega_r^2$, (2) yields the following solution:

$$\omega_r = \pm \frac{\left\{ \frac{N_e}{N_o}\left(1-\frac{A_e}{2}-\frac{A_p}{2}\right)\frac{k^2c^2}{\omega_{pe}^2}\Omega_e + \Omega_o\left[\frac{A_o}{\beta_{\|o}} - \frac{2\Omega_o(\Omega_o \mp kU_o)}{k^2\alpha_{\|o}^2}\right]\right\}}{\left(1+\frac{2\Omega_o^2}{k^2\alpha_{\|o}^2}\right)}, \tag{3}$$

$$\gamma \approx \frac{\sqrt{\pi}\Omega_o \exp(-\eta_{or}^2)}{(1+2\Omega_o^2/k^2\alpha_{\|o}^2)}\left[\frac{\beta_{\perp o}}{\beta_{\|o}}\frac{(\omega_r - kU_o)}{k\alpha_{\|o}} \mp \frac{A_o}{\beta_{\|o}}\frac{\Omega_o}{k\alpha_{\|o}}\right], \tag{4}$$

where $\eta_{or} = \eta_o(\omega = \omega_r)$.

When the second term in the curly brackets is neglected, (3) becomes very similar in structure to the dispersion relation for the usual helicon mode,

$$\omega_H = \frac{k^2c^2}{\omega_{pe}^2}\Omega_e, \tag{5}$$

in electron–proton plasma. Eq. (3) shows that electron dynamics dominates the interaction between the electromagnetic waves and the multi-ion plasma.

We have computed the real frequency, ω_r, and the growth rate, γ as given by (3) and (4) by using *Mathematica* for both RH and LH polarized modes. For parameters listed in the caption of Figs. 1 and 2, we find that the helicon mode instability occurred for the RH mode only. The assumption of treating the O^+ ion beam as hot breaks down at smaller values of normalized wavenumbers, kV_{A_p}/Ω_o where the peak in the growth rate occurs. Therefore, in Figs. 1 and 2 we have shown only those portions of the growth rate (and the corresponding real frequency) curves where all the assumption made in the analysis are satisfied. The ranges of real frequencies and growth rate increase when A_o is increased (cf. Curves 1–3 in Figs. 1a and b). A positive (negative) value of proton anisotropy has a destabilizing (stabilizing) effect (cf. Curves 4 and 5). Figs. 2a and b show that increases in M and R have destabilizing effects on the instability (cf. curves 1–3). Positive (negative) value of electron anisotropy has a destabilizing (stabilizing) effect (cf. curves 4 and 5).

2.2. Neutralized O^+ ion beam

We consider an ionospheric O^+ ion beam passing through the plasma sheet region where the current carried by O^+ ions is neutralized by the equilibrium electron drift velocity satisfying the condition, $U_e = -N_oU_o/N_e$ (once again $U_p = 0$). Such a situation corresponds to no net field-aligned current in the system in the equilibrium state. Then, once again treating electrons and protons as cold, and the O^+ ion beam as hot, and further considering low frequencies (compared to plasma frequencies), (1) can be simplified to

$$k^2V_{A_p}^2\left(1-\frac{A_e}{2}-\frac{A_p}{2}\right) + R\Omega_o^2\left[\frac{A_o}{\beta_{\|o}} - \frac{2\Omega_o^2}{k^2\alpha_{\|o}^2}\right]$$

$$\mp R\Omega_o(\omega - kU_o)\left(1+\frac{2\Omega_o^2}{k^2\alpha_{\|o}^2}\right) - \omega^2$$

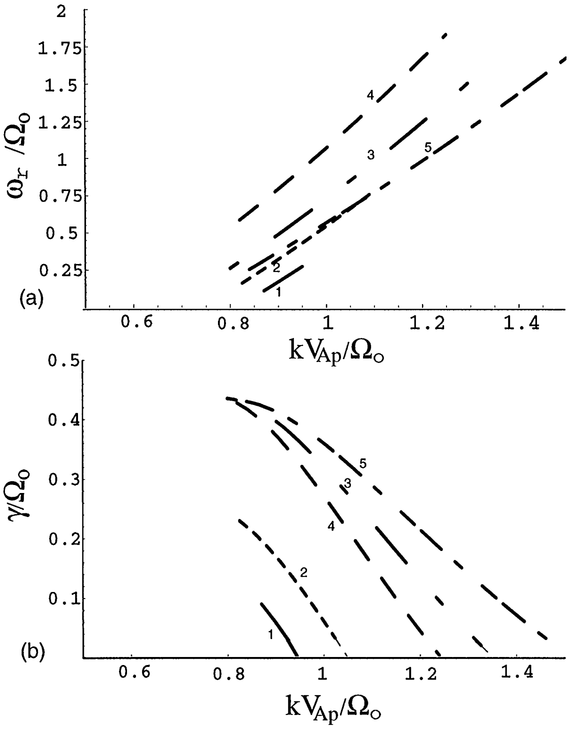

Fig. 1. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{A_p}/Ω_o for the helicon mode instability driven by non-neutralized O^+ ions in the CPS region for $M = U_o/V_{A_p} = 0.25$, $R = 1.0$, $A_e = A_p = 0$, and $\beta_{\|o} = 3.5$. The curves 1–3 are for $A_o = (\beta_{\|o} - \beta_{\perp o}) = 0.1$, 0.5 and 2.0, respectively. The curves 4 and 5 are for $A_o = 2$, $M = 0.25$, $R = 1.0$, and $A_p = -0.5$ and 0.5, respectively. For the parameters considered here as well as in Fig. 2, the LH mode instability does not exist.

$$-i\sqrt{\pi}R\Omega_o^2\exp(-\eta_o^2)$$

$$\times\left[\frac{\beta_{\perp o}}{\beta_{\|o}}\frac{(\omega - kU_o)}{k\alpha_{\|o}} \mp \frac{A_o}{\beta_{\|o}}\frac{\Omega_o}{k\alpha_{\|o}}\right] = 0. \tag{6}$$

Once again, considering $\omega^2 \ll R\Omega_o(\omega - kU_o)$, and writing $\omega = \omega_r + i\gamma$, where $\gamma^2 \ll \omega_r^2$, (6) yields the following solution:

$$(\omega_r - kU_o) = \pm \frac{\left\{ \frac{N_e}{N_o}\left(1-\frac{A_e}{2}-\frac{A_p}{2}\right)\frac{k^2c^2}{\omega_{pe}^2}\Omega_e + \Omega_o\left[\frac{A_o}{\beta_{\|o}} - \frac{2\Omega_o^2}{k^2\alpha_{\|o}^2}\right]\right\}}{\left(1+\frac{2\Omega_o^2}{k^2\alpha_{\|o}^2}\right)}, \tag{7}$$

$$\gamma \approx \frac{\sqrt{\pi}\Omega_o \exp(-\eta_{or}^2)}{(1+2\Omega_o^2/k^2\alpha_{\|o}^2)}\left[\frac{\beta_{\perp o}}{\beta_{\|o}}\frac{(\omega_r - kU_o)}{k\alpha_{\|o}} \mp \frac{A_o}{\beta_{\|o}}\frac{\Omega_o}{k\alpha_{\|o}}\right]. \tag{8}$$

In evaluating (8), we must make use of (7) for substituting the value of ω_r. From (7) and (8), it is clear that oxygen ion Mach number does not affect the instability property of the modes to the leading order. The instability in this

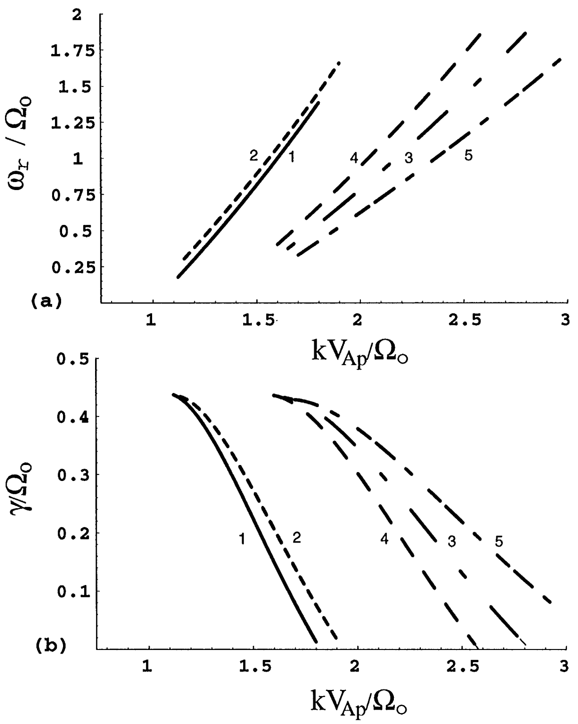

Fig. 2. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{A_p}/Ω_o for the helicon mode instability driven by non-neutralized O^+ ions in the CPS region for $A_e = A_p = 0$, $A_o = 2.0$, and $\beta_{\|o} = 3.5$. Curves 1 and 2 are for $R = 2.0$, and $M = 0.05$ and 0.2, respectively. Curve 3 is for $M = 0.2$, and $R = 4.0$. Curves 4 and 5 are for $A_e = -0.5$ and 0.5, respectively.

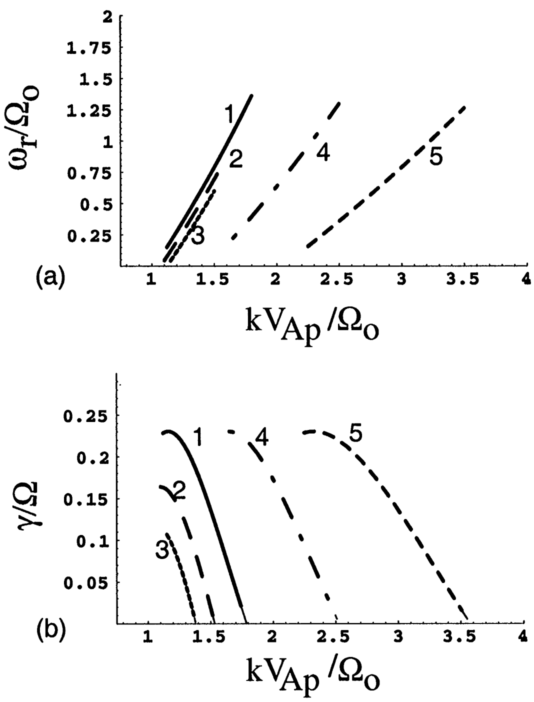

Fig. 3. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{A_p}/Ω_o for the helicon mode instability driven by neutralized O^+ ions in the CPS region for $A_e = A_p = 0$, and $\beta_{\|o} = 3.5$. Curves 1–3 are for $R = 1.0$, and $A_o = 2.0$, 1.5, and 1.0, respectively. Curves 4 and 5 are for $A_o = 2.0$, and $R = 4$ and 8, respectively. To the leading order, growth rates are independent of the Mach number M of the neutralized O^+ ion beam.

case is driven by the anisotropy. The O^+ ion Mach number will affect these modes only when the assumption $\omega^2 \ll R\Omega_o(\omega - kU_o)$ is relaxed. From (7) and (8), it is clear that both RH and LH modes can be exited by the pressure anisotropy.

We have numerically computed the real frequency and the growth rate from (7) and (8) for the helicon modes in the presence of neutralized O^+ ion beam in the near-Earth central plasma sheet region. The results are shown in Figs. 3a and b for the right-hand mode only. As in the non-neutralized beam case, an increase in the pressure anisotropy, A_o of the O^+ ion beam has a destabilizing effect (cf. Curves 1–3). An increase in the parameter R leads to an increase in the unstable wave numbers (cf. curves 1, 4, and 5). Therefore, the wave mode will be destabilized by an increase in the oxygen ion number density. In general, for the case of neutralized O^+ ion beam, both the growth rate and real frequency are smaller as compared to the non-neutralized O^+ ion beam case (cf. Figs. 1–3). Further, the instability occurs for higher values of the normalized wave number in the case of neutralized O^+ ion beam as compared to the non-neutralized O^+ ion beam case. Therefore, the unstable modes for the neutralized beam case would have shorter wavelengths as compared to the latter case.

3. Injection of O^+ ions into the Ring Current

Our analysis shows that the presence of hot ionospheric O^+ ions in the central plasma sheet (CPS) may excite helicon mode instability during any substorm phase. For the case of a neutralized O^+ ion beam, when both the charge and the current neutrality conditions are satisfied in the equilibrium state, modes with both RH and LH polarizations could become unstable due to pressure anisotropy. The Mach number of the hot O^+ ion beam has no effect, to the leading order, on the excitation of the helicon modes. On the other hand, for the case of a non-neutral hot O^+ ion beam passing through the plasma sheet region (corresponding to a finite field-aligned current in the equilibrium state), only the helicon modes with RH polarization are found to be excited. Both the Mach number and the pressure anisotropy of hot O^+ ion beam have strong destabilizing effect on the excitation of the helicon mode in this case.

The helicon modes studied here have some similarities with the finite gyroradius firehose modes studied by Davidson and Völk (1968) and Yoon et al. (1993). Both wave modes have finite real frequencies and both are destabilized by the pressure anisotropy having $\beta_{\parallel}$ greater than $\beta_{\perp}$. The similarity of both wave modes is probably due to the breaking of MHD constrain, i.e., the non-idealness. For the modes discussed by Davidson and Völk (1968) and Yoon et al. (1993) the non-idealness is introduced by finite Larmor radius effects. In our case, however, the cause of non-idealness is the partial cancellation of the electron Hall current in the presence of unmagnetized or partially magnetized O^+ ions.

Based on observations and theoretical models, we consider the following parameters for the central plasma sheet in the region $X \sim -10$ to -15 R_E: $A_0 = 0.1$–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.

Figs. 1–3 show that the range of excited real frequencies, growth rates, and unstable wavelengths, $\lambda = 2\pi/k$, are, respectively, ω_r=(0.1–1.9) Ω_o=(1.0–19.0) mHz, γ= (0.05–0.45) Ω_o=(0.5–4.5) mHz, and $\lambda = V_{A_p}/(0.8$–$3.5)$ Ω_o=(0.5–2) 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 wavelengths $\sim$ (0.5–2) R_E in the CPS. The typical e-folding time of the instability is about 3 to 15 min at wavelengths of $\lambda \approx$ 0.5–2 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 hot O^+ ion beams in the CPS region may have some interesting consequences for the substorm process. The large scale fluctuating z and y components of B, i.e., δB_z and δB_y, associated with the helicon modes could twist the equilibrium magnetic field into flux ropes. This property of the helicon modes could provide an explanation to the GEOTAIL observation of oxygen ion bursts associated with multiple flux ropes in the distant magnetotail (Wilken et al., 1995). The δB_z fluctuations associated with large amplitude helicon modes could produce localised minimal in the z component of the magnetotail magnetic field near the neutral axis. These localized minima (separated by the wavelength of the excited modes) are likely to be the potential site for the excitation of the tearing mode instabilities which could lead to the onset of the expansion phase of substorms. Moreover, the low-frequency turbulence due to the helicon modes could scatter electrons trapped in the CPS region, thus further enhance the growth of the tearing modes at these sites. Furthermore, 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, 1972; Tsurutani et al., 1985, 1987; Bauer et al., 1995).

As pointed out in the introduction, oxygen ions at times are found to dominate the energy density of the storm-time ring current (Hamilton et al., 1988, Daglis, 1997). The origin of these oxygen ions is one of the major puzzles for magnetic storm research (Tsurutani et al., 1997). It has recently been noted that O^+ and H^+ ions in the dayside boundary layer/cusp are heated/accelerated essentially all the time by intense broadband plasma waves. During southward interplanetary magnetic field events, these ions could be convected in anti-sunward direction across the polar cap and into the plasma sheet (Tsurutani et al., 1998). There can also be a direct injection of O^+ ions from the auroral region as suggested by Daglis et al. (1994a). We speculate that if the oxygen ions form anisotropic beams in the inner plasma sheet as discussed here, they provide an ideal situation for the excitation of the helicon mode instability and substorm onset. These O^+ ions would energized, along with the H^+ and other minor ions, during the substorm expansion phase. Consequential injection of this plasma inward into the Earth's night side magnetosphere by the storm electric fields could then lead to enhanced oxygen ion fluxes in the storm-time ring current. The enhancement of the O^+ ions in the ring current region could have a strong controlling effect on the excitation of electromagnetic ion cyclotron (EMIC) waves, and thus on the ring current decay during storms (Thorne and Horne, 1997).

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