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# Excitation of plasma sheet instabilities by ionospheric $O^+$ ions

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**Abstract.** It is shown that the presence of ionospheric $O^+$ ions in the inner central plasma sheet (ICPS) during growth phase of the substorms can excite nonresonant low-frequency, long wavelength RH mode instability under certain conditions. For the ICPS parameters during enhanced convection events, the excited modes have real frequencies of (0.1 - 5.0) mHz, and the typical maximum growth rates of $\sim$ (0.1 - 4.0) mHz with corresponding wavelengths of $\sim$ (1 - 30) $R_E$ ( $R_E$ being the Earth's radius). The excited low-frequency modes are expected to saturate to the maximum level of $\delta B^2/B_0^2 \approx (2.5\times10^{-3} - 0.25)$, where $\delta B$ and $\delta B_0$ are the fluctuating magnetic field associated with the unstable modes, and the equilibrium magnetic field respectively. The large amplitude magnetic field fluctuations due to the nonresonant low-frequency instability driven by $O^+$ ions could twist the ICPS magnetic field into flux ropes, and also produce localised minima, in the magnetotail magnetic field near the neutral axis, which can be the potential sites for the excitation of the tearing modes leading to substorm onset.

## Introduction

Recent observations suggest that heavy ions of ionospheric origin can, some times, dominate the composition of the outer magnetosphere and the plasma sheet region [*Peterson et al.*, 1981; *Sharp et al.*, 1981; *Daglis et al.*, 1991, 1993, 1994]. Earlier observations from S3-3 indicated the presence of large fluxes of trapped $O^+$ ions in the outer magnetosphere and of precipitating $O^+$ ions in the auroral zone [ *Shelley et al.*, 1982]. Upward beams have been identified with active aurora and are considered to play an important role in the auroral processes. Similarly, the upward flow of high-density low-velocity $O^+$ ions from dayside cusp/cleft ionosphere is found to increase significantly during times of enhanced magnetospheric convection [*Yau et al.*, 1986]. Transport of $O^+$ ions from the cusp/ cleft ionosphere to the nightside magnetosphere has been studied by *Delcourt et al.* [1989] and *Cladis and Francis* [1992]. *Cladis and Francis* [1992] found that after about 1.7 hours from the commencement of an enhanced convection event, the $O^+$ ion flux in the near-Earth plasma sheet increased drastically and it resembled the $O^+$ fluxes measured with AMPTE IRM and CCE spacecraft at period preceding substorms [*Daglis et al.*, 1990]. Further, the parallel pressure of the $O^+$ ions exceeded the transverse pressure as well as the magnetic pressure at $X < -8R_E$. It is interesting to note that the $O^+$ ions exert pressure in the region of the plasma sheet where the near-Earth neutral line is expected to form [*Kistler et al.*, 1992].

*Baker et al.* [1982] have proposed that the enhanced densities of ionospheric $O^+$ ions in some localized region in the plasma sheet would favor the excitation of the ion tearing instability which can lead to the onset of the substorm [*Schindler*, 1974]. The reason for this is that since $O^+$ ions have larger gyroradius than $H^+$ ions, they become demagnetized (non-gyroscopic) earlier in the curved magnetic field of the growth-phase plasma sheet, and therefore lower the instability threshold for the ion tearing mode.

*Cladis and Francis* [1992] suggested a mechanism for the triggering of substorm onset on the basis of the changes of the electric and magnetic fields resulting from the arrival of the $O^+$ ions in the plasma sheet. According to their model, increased $O^+$ parallel pressure in the near-Earth magnetotail could alter the magnetic and electric fields leading to the development of shears in the convection velocity near the flanks of the $O^+$ injection region. The substorm may be triggered by velocity shear instabilities that effectively create anomalous resistivity in the near-midnight of the inner central plasma sheet.

In this paper, we study the stability of the near-Earth ($X \approx$ -10 $R_E$ to -15 $R_E$ ) plasma sheet in the presence of ionospheric $O^+$ ions. We take into account the pressure anisotropy of the $O^+$ ions as well as their drift parallel to the magnetic field. The stability analysis is restricted to the low frequencies (wave frequency, $\omega$, much smaller than the plasma frequencies, $\omega_{pj}$), and the long wavelengths ( i.e., longer than the gyroradii of protons as well as oxygen ions).

## Low-Frequency Electromagnetic Modes

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 and Buti*, 1976 ] in standard notation,

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

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where $Z(\eta_j)$ is the well known plasma dispersion function with the argument $\eta_j = (\omega - kU_j \pm \Omega_j)/k\alpha_{\parallel j}$, $\omega_{pj} = (4\pi q^2 N_j/m_j)^{1/2}$ and $\Omega_j = q_j B_0/m_j c$ are the plasma and the gyrofrequency of the $j$th species, where $j = e$, $p$ and $o$ for electrons, protons and the oxygen ions respectively, $U_j$ is the drift velocity of the $j$th species, and $\alpha_{\perp j}$ and $\alpha_{\parallel j}$ are respectively the perpendicular and parallel thermal velocities with respect to $\mathbf{B}_0$. The $\pm$ sign in $\eta_j$ denotes the RH (+ sign) and the LH (− sign) modes. In writing (1), we have taken the distribution functions as drifted bi-Maxwellians.

For the case of $\eta_j \gg 1$ for each species, and noting that lighter electrons maintain charge and current neutrality in equilibrium but contribute little to the mass average, and using the low-frequency approximation ( compared to the plasma frequencies ) [*Verheest and Lakhina*, 1993 ], (1) can be simplified to,

$$k^2V_A^2 \mp \sum_j \sigma_j \frac{(\omega - kU_j)^2\Omega_j}{\omega - kU_j \pm \Omega_j} + \sum_j \frac{k^2V_A^2\Omega_j^2(\beta_{\perp j} - \beta_{\parallel j})}{2(\omega - kU_j \pm \Omega_j)^2} = 0. \qquad (2)$$

Here $\sigma_j = \rho_j/\sum_j \rho_j$, refers to ratio of the equilibrium mass densities, $\rho_j$, of the different plasma species, normalized to the total mass density, $\sum_j \rho_j$, of the combined plasma, and $\beta_{\perp j}$ and $\beta_{\parallel j}$ are respectively the parallel and the perpendicular plasma beta for the $j$th species, and $V_A = (B_0^2/4\pi\sum_j \rho_j)^{1/2}$ is the Alfvén veolocity with respect to the total mass density.

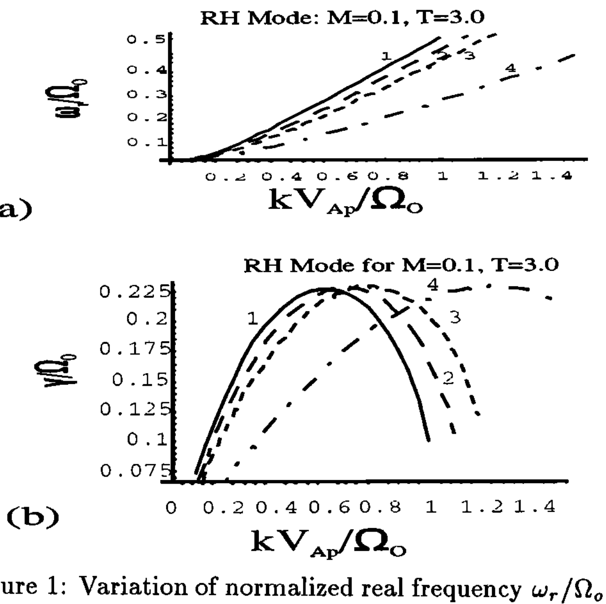

Figure 1: Variation of normalized real frequency $\omega_r/\Omega_o$ (a), and growth rate $\gamma/\Omega_o$ (b) versus normalized wavenumber $kV_{Ap}/\Omega_o$ for the RH mode instability driven by $O^+$ ions in the ICPS region for $M = U_o/V_{Ap} = 0.1$ and $T = (\beta_{\parallel o} - \beta_{\perp o}) = 3.0$. The curves 1, 2, 3, and 4 are respectively for $R = \rho_o/\rho_p = 0.1$, 0.5, 1.0, and 5.0. For these parameters considered here as well as in Figure 2, the LH mode instability does not exist.

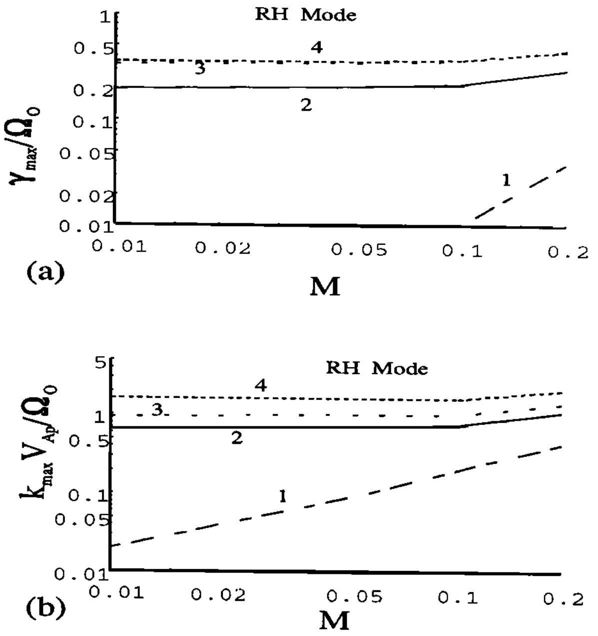

Figure 2: Variation of normalized maximum growth rate $\gamma_{max}/\Omega_o$ (a), and corresponding normalized wavenumbers $k_{max}V_{Ap}/\Omega_o$ (b) versus Mach number M for the RH mode instability driven by $O^+$ ions in the ICPS region for $R = 1.0$, and $T = 2.0$, 3.0, and 4.0 for the curves 1, 2, and 3 respectively. The curve 4 is for $T = 4.0$ and $R = 5.0$.

For the special case of $\omega \ll \Omega_o$, and $U_p = 0$, (2) simplifies to

$$\left(\omega - \frac{\rho_o}{\rho_p + \rho_o}kU_o\right)^2 = k^2V_A^2\left[1 + \sum_j \frac{(\beta_{\perp j} - \beta_{\parallel j})}{2} - \frac{\rho_o}{\rho_p + \rho_o}M^2\right], \qquad (3)$$

where $M = U_o/V_{Ap}$ is the oxygen ion Alfvén Mach number with respect to proton mass density. Equation (3) predicts a *fire-hose* type instability provided

$$1 + \sum_j \frac{(\beta_{\perp j} - \beta_{\parallel j})}{2} - \frac{\rho_o}{\rho_p + \rho_o}M^2 \le 0 \qquad (4)$$

The equality sign in (4) corresponds to the marginally stable state. For M = 0, the instability criterion (4) becomes identical with the *fire-hose* instability criterion. In particular, for isotropic electrons and protons, and for $M = 0$, the instability is excited for $\beta_{\parallel o} > 2 + \beta_{\perp o}$. When all the species are isotropic, instability is possible for $M > 1 + \rho_p/\rho_o$.

The dispersion relation (2) is solved numerically by *Mathematica*, for the case of $U_p = 0$ and isotropic electrons and proton, and without *a priori* assumption of $\omega$ to be much smaller than $\Omega_o$, for parameters relevant to the near-Earth ($X \sim$ -10 $R_E$ to -15 $R_E$ ) inner central plasma sheet (ICPS) region. For a given set of parameters, (2) was solved for both the RH mode and the

LH modes. For the parmeters considered here, the LH mode can not exists as the assumption of $\eta_o \gg 1$ was always violated. Hence, the results for RH modes only are shown in Figures 1 and 2. It was necessary to cut-off a particular curve whenever any assumption made in the analysis is violated.

Figures 1a and 1b show that the real frequencies decrease with the increase of the parameter $R = \frac{\rho_o}{\rho_p}$ (cf. curves 1-5, Figure 1a). The growth rates attain the maximum value, say $\gamma_{max}/\Omega_o$ for certain values of wavenumbers, say $k_{max}V_{Ap}/\Omega_o$. The peak growth rates remain more or less the same, but the range of unstable wavenumbers increases and gets shifted towards larger $k$s as $R$ increases (cf. curves 1-5, Figure 1b).

Figures 2a and 2b show that both $\gamma_{max}/\Omega_o$ and $k_{max}V_{Ap}/\Omega_o$ are increased by the increase of the parameters $M$, $T = (\beta_{\|o} - \beta_{\perp o})$ (cf. curves 1, 2, and 3), and $R$ (cf. curves 3 and 4). It is to be noted that for the parameters of the curves 1 and 2, the usual *fire-hose* instability, driven by pressure anisotropy alone, is stable.

## Discussion

The ionosphere is a rather variable source of heavy ions, and the two most important ionospheric outflow regions are the dayside cusp/cleft and the auroral region [ *Hultqvist*, 1991; *Lockwood et al.*, 1985; *Cladis*, 1986; *Möbius et al.*, 1987; *Cladis and Francis*, 1992; *Daglis et al.*, 1994]. Computations of *Cladis and Francis* [1992] show that parameter $T \sim$ 1 - 5 in the region $X \sim$ -10 $R_E$ to -15 $R_E$ within about two hours of the commencement of an enhanced convection event. *Daglis et al.* [1991] have observed total pressure anisotropy including all ions of $\sum_j(P_{\|j} - P_{\perp j}) \approx (0.1 - 2.5)$ keV cm$^{-3}$ during growth phase of a substorm. Assuming $B_0 = 10$ nT, this gives $T_{total} = \sum_j(\beta_{\|j} - \beta_{\perp j}) \approx (1 - 25)$. Recent study by *Lennartsson* [1994] gives indications that, atleast during some occasions, $O^+$ ion can develop significant pressure anisotropy in the ICPS region. Hence our choice of the parameter $T \simeq (1 - 4)$, which includes only the $O^+$ ion contribution, appears to be reasonable.

The number density of $O^+$ ions in the inner central plasma sheet is quite variable. *Lennartsson and Shelley* [1986] found the average $O^+$ density in this region to be about 0.2 cm$^{-3}$ during highly disturbed times. Since in the inner plasma sheet, $N_p \approx 0.5$ cm$^{-3}$ on an average, the parameter $R$ could have value of about 6.4 as an upper limit. Therefore our choice of $R = (0.1 - 5)$ appears to be reasonable.

Measurements of $O^+$ ion flow velocity in the plasma sheet region are sparse. Infact most of the studies assume either implicitly or explicitly that MHD approximation holds good in this region, thereby implying that both the protons and the $O^+$ ions have the same drift velocity. If this be the case then energies of the $O^+$ ions and protons should on the average differ by a factor of 16. Several observations indicate that this conditions is not satisfied all the time. *Lennartsson and Sharp* [1982] and *Lennartsson* [1994] have found that $H^+$ and $O^+$ ions have similar mean enregies in the central plasma sheet during disturbed conditions although there is a lot of scatter in the data. Coming to the measurements of flow velocities, *Peterson et al.* [1981] have reported $U_p \sim 31$ km s$^{-1}$ and $U_o \sim 43 \pm 60$ km s$^{-1}$ with large uncertainties. *Candidi et al.* [1982] and *Orsini et al.* [1985] have reported flow velocities of $O^+$ ions as varying between $U_o \sim (50 - 200)$ km s$^{-1}$ in the magnetotail boundary layer and plasma lobe, and $U_o \sim (20 - 120)$ km s$^{-1}$ in the plasma sheet respectively. *Stokholm et al.* [1985] have observed cold anisotropic $O^+$ ion beams in the plasma sheet region with $U_o \sim 20 - 60$ km s$^{-1}$. However, in the absence of simultaneous measurement of $U_p$, it is rather difficult to find the relative drift speed between $O^+$ ions and protons in the plasma sheet region. We feel that considering $|U_o - U_p| \approx 10 - 60$ km s$^{-1}$ in the ICPS may be quite reasonable. Then, for $B_0 = 10$ nT and $N_p = 0.5$ cm$^{-3}$, we get $V_{Ap} \approx 300$ km s$^{-1}$. This would lead to $M = 0.03 - 0.2$ in the ICPS region.

Figures 1 and 2 clearly show that the range of excited real frequencies, maximum growth rates, and unstable wavelengths, $\lambda = 2\pi/k_{max}$, are respectively $\omega_r = (0.01 - 0.5)\ \Omega_o = (0.1 - 5.0\ )$ mHz, $\gamma_{max} = (0.01\text{–}0.4)\ \Omega_o = (\ 0.1 - 4.0\ )$ mHz, and $\lambda = V_{Ap}/(0.05 - -1.5)\Omega_o = (1 - 30\ )\ R_E$ for $M = (0.01 - 0.1)$, $R = 1 - 5$, $T = 2 - 4$, $B_0 = 10$ nT and $N_p = 0.5$ cm$^{-3}$. Hence the instability would preferentially excite low-frequency waves with wavelenghts $\sim (1 - 30)\ R_E$ in the ICPS. The typical e-folding time of the instability is about 4 to 10 minute at shorter wavelengths of $\lambda \approx 1$ to 5 $R_E$, which is reasonably short, and these modes could attain saturation as the enhanced convection events may last for a few hours. The longest wavelength modes with $\lambda \approx 20$ to 30 $R_E$, however, may not attain saturation as their e-folding time is $\sim$ a few hours.

Generalising the analysis of *Verheest and Lakhina* [1991] to the case of anisotropic plasmas, an upper estimate for the saturation of the wave magnetic field due to the nonresonant Alvénic instabilities is given by,

$$\frac{\delta B^2}{B_0^2} = \frac{1}{2}\left[1 - \frac{1+R}{RM^2 + (1+R)\sum_j(\beta_\| - \beta_\perp)/2}\right] \quad (5)$$

where $\delta B$ is the fluctuating magnetic field associated with the unstable modes. The term on the right hand side of (5) is always positive (cf. (4) ) for the unstable modes. To give an idea about upper levels of wave magnetic field for the unstable modes, (6) predicts for $M = 0.1$ and $R$=1 - 5, $\delta B^2/B_0^2 \approx (2.5 - 4.1) \times 10^{-3}$ for $T = 2$ and $\delta B^2/B_0^2 \approx 0.25$ for $T = 4$. Recently *Bauer et al.* [1995] have done an extensive statistical survey of the low-frequency waves in the frequency range 0.1 mHz to 8 Hz in the near Earth's plasma sheet between 9 and 20 $R_E$. From the various observed power spectra given by *Bauer et al.* [1995] (cf. their Figures 9 – 12) and taking $B_0 = 10$ nT as an average magnetic field value in the ICPS, we derive $\delta B^2/B_0^2 \approx (0.001 - 0.1)$ for the RH modes in the frequency range of 0.1

to 10 mHz. This ratio is in good agreement with our estimates. It is tempting to associate some of the low-frequency turbulence observed by *Bauer et al.* [1995] to the instability mechanism discussed here. We would, however, caution that *Bauer et al.* [1995] assumed that all the ions were protons while computing the moments of the distribution functions.

It is very likely that the low-frequency modes due to nonresonant instability driven by the $O^+$ ions in the ICPS region could grow to large amplitudes. This fact might have some interesting consequences for the substorm processes. Firstly the large scale fluctuating $z$ and $y$ components, i.e., $\delta B_z$ and $\delta B_y$, associated with the low-frequency modes excited by $O^+$ ions could twist the equilibrium magnetic field and may give rise to flux ropes. Secondly, the large amplitude $\delta B_z$ could produce localised minima, in the $z$ component of the 2D equilibrium magnetotail magnetic field near the neutral axis separated by the wavelength of the excited modes, which can be the potential sites for the excitation of the tearing modes leading to the onset of the expansion phase of the substorm.

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