The role of anisotropic ring current ions in the excitation of low-frequency waves during magnetic storms

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Abstract. The compositional variations of H^+ and O^+ ions during the intense geomagnetic storms have considerable effects on ring current plasma dynamics. The storm time ring current is populated with energetic particles having anisotropic distribution functions that can provide free energy for the excitation of different types of plasma waves. A four component model has been developed to study the effect of thermal anisotropy of H^+ and O^+ ions on the excitation of low-frequency quasi-electrostatic waves. A dispersion relation is derived in the ring current plasma consisting of isotropic electrons, background cold protons, and energetic protons and oxygen ions, both having Dory-Guest-Harris (DGH) type loss cone distributions. The dispersion relation is solved numerically for storm time ring current parameters. These modes can scatter ring current ions into the atmospheric loss-cone leading to their precipitation into the ionosphere, thus, providing a ring current decay mechanism complementary to the charge exchange.

Index Terms. Anisotropic ions, low-frequency waves, magnetic storms, ring current.

1. Introduction

Magnetic storms are characterized by a sudden enhancement in the ring current circulating around the Earth. This current is transported by protons, oxygen ions, and electrons and it is located between 2 to 7 R_E (Gonzalez et al., 1994 and references therein), where R_E is the radius of the Earth. The compositional variations of these energetic ions (H^+, O^+ ions) in the magnetospheric plasma during geomagnetically disturbed times can have considerable effect on the ring current dynamics. The storm time terrestrial ring current gets populated with energetic particles with anisotropic distributions that can provide free energy for the excitation of different types of plasma waves. Recent observations show that the thermal anisotropy of the ring current particles could be a free energy source for the excitation of the waves in the ring current region (Horne and Thorne, 1994). It is known that, the ring current decay is mainly due to the charge exchange with exospheric neutrals, Coulomb collisions with the thermal plasma, and wave particle interactions. The enhanced charge exchange loss of ring current ions having small pitch angles (Cornwall, 1977) deepens the loss cone and increases the anisotropy of the drifting ion distributions making them more unstable to the generation of the plasma instabilities.

The Electrostatic ion cyclotron (EIC) waves have been observed on the auroral field lines by many satellites namely S3-3 (Kinter et al., 1978; Temerin et al., 1979), Viking (Andre et al., 1987), ISEE-1 (Cattell et al., 1991) and Polar (Mozer et al., 1997). For the excitation of the EIC waves, currents, ion beams, and velocity shear have all been proposed to provide the free energy for the instability (Lakhina, 1987; Ganguli et al., 1988). In the ring current region a quasi-electrostatic instability can be excited by loss-cone distribution of protons (Coroniti, 1972; Bhatia and Lakhina, 1980; Singh et al., 2004). Recently Singh et al. (2005) have studied the quasi electrostatic low-frequency instabilities excited by the anisotropic O^+ ions in the ring current region. They found that the waves with frequency near the cyclotron harmonics of the oxygen ions can be excited by the anisotropic oxygen ions.

In the present paper we study the obliquely propagating modes with frequencies greater than the proton cyclotron frequency. Using the energetic proton and oxygen ions as a free energy source, we study these modes in the ring current region during the storm. Ring current plasma is considered to consist of Maxwellian distributed electrons and the background protons, and energetic protons and oxygen ions with Dory-Guest-Harris (DGH) type of distribution. In the next section, we present the theoretical model.

2. Theoretical model

We consider the four-component plasma consisting of Maxwellian distributed electrons and the background protons, and loss cone type distributed proton and oxygen ions with Dory-Guest-Harris (DGH) type of distributions (Coroniti et al., 1972, Singh et al, 2004, 2005) given by

$$f_s = \sum_{s=p,o} \frac{N_s}{\pi^{3/2} J_s! \alpha_{\parallel s} \alpha_{\perp s}^2} \left(\frac{v_{\perp s}}{\alpha_{\perp s}} \right)^{2J_s} Exp\left[-\left(\frac{v_{\perp s}^2}{\alpha_{\perp s}^2} + \frac{v_{\parallel s}^2}{\alpha_{\parallel s}^2} \right) \right] \quad (1)$$

Where

$$\alpha_{\perp s}^2 = \frac{\alpha_{\perp s0}^2}{J_s + 1} = \mu_s^{-1}, \quad \alpha_{\parallel s}^2 = \frac{2T_{\parallel s}}{m_s}, \quad \alpha_{\perp s0}^2 = \frac{2T_{\perp s}}{m_s}$$

Here J_s = 0, 1, 2… is the loss-cone index defining the depth of the loss cone. m_s, $T_{\parallel s}$ and $T_{\perp s}$ are the mass, parallel and perpendicular temperatures of the species, 's' respectively. We treat the response of electrons to the perturbation as fully electromagnetic, and that of protons and oxygen ions as electrostatic.

In this analysis we have considered the electrons and background protons to be isotropic. This assumption is for the sake of mathematical simplicity and to emphasize the effect of energetic proton and oxygen ions on the excitation of waves. In our analysis we assume the response of background protons, energetic protons and oxygen ions to the perturbations as if they are unmagnetized ($\omega > \omega_{co}, \omega_{cb}, \omega_{cp}$) in the sense that they follow the straight line orbits. This is justified because perturbations are of much higher frequency than the cyclotron frequency of the protons and oxygen ions and on the perturbation time scale, the ambient magnetic field does not distort their orbits significantly. Further, the electrons are treated as magnetized since the wave frequency is much smaller than the electron cyclotron frequency, i.e., $\omega \ll \omega_{ce}$. The response of the electrons is taken as fully electromagnetic, i.e., $\omega_{pe}^2/c^2k^2 \gg 1$, while background protons, energetic protons and oxygen ions are considered to be electrostatic, i.e., $\omega_{pb}^2/c^2k^2 \ll 1$, $\omega_{pp}^2/c^2k^2 \ll 1$ and $\omega_{po}^2/c^2k^2 \ll 1$. Under the above assumptions, a dispersion relation for the waves propagating obliquely to the magnetic field $\mathbf{B}_0 \parallel \mathbf{z}$ can be obtained by solving the linearized Vlasov equation along with Maxwell's equations and is written as (Coroniti et al., 1972, Davidson et al., 1977, Bhatia and Lakhina, 1977, 1980, Singh et al, 2004, 2005)

$$1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\left[\frac{1-I_0(\lambda_e)e^{-\lambda_e}}{\lambda_e}\right]+\frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{\omega_{pe}^2}{c^2k^2}\left[\frac{\left[\{I_0(\lambda_e)-I_1(\lambda_e)\}e^{-\lambda_e}\right]^2}{1+\beta_e\{I_0(\lambda_e)-I_1(\lambda_e)\}e^{-\lambda_e}}\right]$$
$$-\frac{k_\parallel^2}{k_\perp^2}\frac{\omega_{pe}^2}{\omega^2}\frac{I_0(\lambda_e)e^{-\lambda_e}}{1+\frac{\omega_{pe}^2}{c^2k^2}I_0(\lambda_e)e^{-\lambda_e}}-\frac{\omega_{pb}^2}{k^2\alpha_b^2}Z'(\xi_b)-$$
$$\sum_{s=p,o}\frac{2\sqrt{\pi}\,\omega\,\omega_{ps}^2}{k_\perp k^2\alpha_{\perp s}^{2J_s+2}}\frac{(-1)^{J_s}}{J_s!}\frac{d^{J_s}}{d\mu_s^{J_s}}\left[\mu_s^{1/2}\{Z'(\xi_s)+S'(\xi_s)-C\}\right]=0 \quad (2)$$

Here, $C=\frac{1}{2\sqrt{\pi}}\frac{d}{d\xi_s}\left(e^{-\xi_s^2}E_i\left(\xi_s^2\right)\right)$,

$Z'(\xi_b)$ and $Z'(\xi_s)$ are derivatives of plasma dispersion function $Z(\xi_b)$ and $Z(\xi_s)$ with their respective to argument, $\xi_b=\omega/k\alpha_b$ and $\xi_s=\omega\sqrt{\mu_s}/k_\perp$. Here, subscript s = p, o refers to energetic proton and oxygen ions respectively, $\mu_s=1/\alpha_{\perp s}^2$ and

$Z(\xi_{b,s})=\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty}\frac{e^{-t^2}}{t-\xi_{b,s}}$ is the plasma dispersion function.

$S(\xi_s)=e^{-\xi_s^2}\int_0^{\xi_s}e^{-\xi_s^2}d\xi_s$ is known as Dawson's Integral.

$E_i\left(\xi_o^2\right)=\gamma+2\ln\xi_o+\sum_{n=1}^{\infty}\frac{\xi_o^{2n}}{n\,n!}$

where γ = 0.5772156649, is an Euler's constant.
Here $\omega_{pl}=(4\pi N_l e^2/m_l)^{1/2}$, $\omega_{cl}=eB_0/cm_l$ respectively are the plasma and cyclotron frequencies of the species *l* (i.e. for electron, background proton, energetic proton and oxygen ions). *ln* indicates the natural logarithm, N_l and m_l are the density and mass of the species *l*. *k* is the wave number, c is the velocity of light, $\lambda_l=k_\perp^2\alpha_l^2/2\omega_{cl}^2$, α_l is the thermal speed of the species *l*. I_0 and I_1 are the modified Bessel functions of order 0 and 1 respectively. Equation 2 is derived under the assumption of, $k_\parallel^2T_{\parallel s}/k_\perp^2T_{\perp s}\ll 1$. It is interesting to note that dispersion relation (2) does not depend on energetic proton and oxygen ion anisotropy explicitly because of this assumption.

Expanding the plasma dispersion function in the limit ξ_b, $\xi_s \ll 1$ and using $\omega=\omega_r+i\gamma$, $\gamma \ll \omega_r$ and neglecting the contribution from the oxygen ions to the real frequency, we obtain expressions for real frequency, ω_r, and growth rate given by,

$$\omega_r=\pm\sqrt{\frac{Q}{P}} \quad (3)$$

$$\gamma=-\frac{\sqrt{\pi}}{Q}\frac{\omega_r^4\omega_{pb}^2}{k^3\alpha_b^3}e^{-\frac{\omega_r^2}{k^2\alpha_b^2}}$$
$$-\sum_{s=p,\,0}\frac{2\pi}{Q}\frac{\omega_r^5\omega_{ps}^2}{k_\perp^2k^2\alpha_{\perp s}^{2J_s+2}}\frac{(-1)^{J_s}}{J_s!}\left[\frac{d^{J_s}}{d\mu_s^{J_s}}\left(\mu_s e^{-\frac{\omega_r^2\mu_s}{k_\perp^2}}\right)\right]=0 \quad (4)$$

Where

$$P=1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\left[\frac{1-I_0(\lambda_e)e^{-\lambda_e}}{\lambda_e}\right]+\frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{\omega_{pe}^2}{c^2k^2}\left[\frac{\left[\{I_0(\lambda_e)-I_1(\lambda_e)\}e^{-\lambda_e}\right]^2}{1+\beta_e\{I_0(\lambda_e)-I_1(\lambda_e)\}e^{-\lambda_e}}\right]+\frac{\omega_{ppb}^2}{k_\perp^2\alpha_b^2} \quad (5)$$

$$Q=\frac{k_\parallel^2}{k_\perp^2}\frac{\omega_{pe}^2\,I_0(\lambda_e)e^{-\lambda_e}}{1+\frac{\omega_{pe}^2}{c^2k^2}I_0(\lambda_e)e^{-\lambda_e}} \quad (6)$$

It can be seen from the growth rate expression (4) that for J_s = 0, the growth rate is negative and the waves are damped. This is due to the fact that there is no free energy source to drive the instability.

3. Numerical results

We perform numerical study separately for 3-component (electrons, background protons and energetic oxygen ions) and 4-component case (electrons, background protons, energetic protons and oxygen ions). In case of 4-component plasma the loss cone index of energetic protons and oxygen ions are considered to be the same. For both the cases, we have numerically calculated the real frequency and the growth rate of the excited modes, for the various storm time ring current parameters. In figure 1a and 1b, the normalized real frequency and growth rates are plotted against normalized wave number $\lambda_o = k_\perp^2 \alpha_{\perp o}^2 / 2\omega_{co}^2$ for different values of loss-cone index. It is found that the normalized growth rate and range of the excited wave numbers increases with the increase of loss-cone index in both the cases. This is expected here, as deeper loss cone provides the larger amount of free energy to excite the waves and increase their growth rate. Also it is found that the corresponding normalized real frequency increases with λ_o but remains unaffected by an increase of anisotropy index in both the cases. It is found that the combination of energetic protons and O^+ ions can excite waves with higher frequencies and larger growth rates in comparison to the case of only energetic oxygen ions. For both the cases we have studied the effect of energetic ion densities on the normalized real frequency and the growth rate of the excited modes for J =1. To study the effect of energetic ion densities we considered fixed density ratio of background protons to electrons and vary n_o/n_e and n_p/n_e ratios in such a way that the quasi neutrality condition would satisfy in each cases. Figure 2a and 2b shows the normalized real frequency and growth rates plotted against normalized wave number $\lambda_o = k_\perp^2 \alpha_{\perp o}^2 / 2\omega_{co}^2$ for different density ratios for the 3 component and 4-component case respectively. It is found the growth rate of the waves increases with the oxygen ion density in case of 3-component plasma. In another case where there is additional free energy source i.e. energetic protons (along with energetic O^+ ions) to excite the waves then energetic protons play the dominant role.

4. Discussion and conclusions

The model presented in this paper deals with the excitation of quasi-electrostatic instabilities with frequencies greater than the proton cyclotron frequency in the ring current region. For the complete numerical computations, we have used the storm time ring current parameters to calculate the growth rate of the excited mode from equation (4) for the different values of loss cone index. In case of 3-component plasma the calculated values of maximum growth rate and their corresponding real frequencies for J=1, 2, 3 are found to be (0.02 Hz, 27 Hz), (0.1 Hz, 35 Hz) and (0.2 Hz, 45 Hz), respectively. The corresponding parallel and perpendicular wavelength for J=1, 2, 3 are respectively calculated to be $\approx$ (160 - 15) km, (130 - 12) km and (110 - 10) km for $T_{\perp o}$=30 keV, B_0 = 500 nT (L ~ 4) (Thorne and Horne, 1997). For the case of 4-component plasma the calculated values of maximum growth rate and the corresponding real frequencies are found to be (0.4, 14 Hz), (1.2, 18 Hz), (2, 22 Hz) for J_s=1, 2, 3 respectively. The corresponding parallel and perpendicular wavelength for J_s=1, 2, 3 are respectively calculated to be $\approx$ (265 - 24) km, (225 - 20) km and (200 - 18) km. It is found that the growth rate of the excited modes increases with the increase in the loss cone depth and concentration of energetic ions.

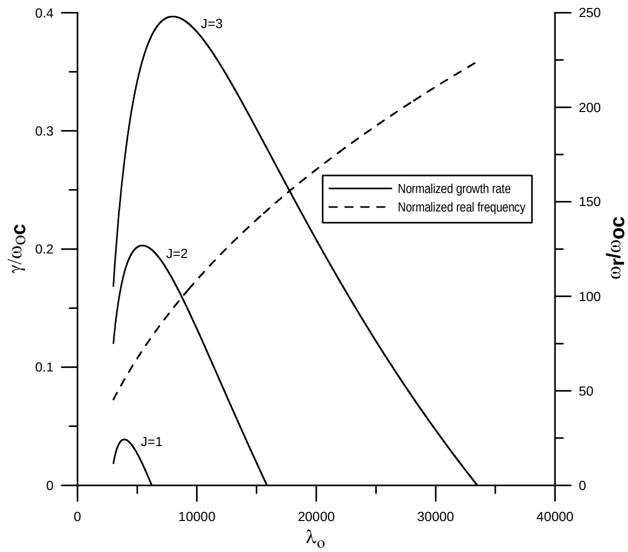

Fig. 1a. Variation of normalized growth rate and real frequency with anisotropic index J (3 - component model). Parameter used here are: n_o/n_e=0.3, n_b/n_e=0.7, ω_{pe}/ω_{ce}=2.0, T_o/T_e=400, T_o/T_b=400, $k_\parallel/k$=0.09.

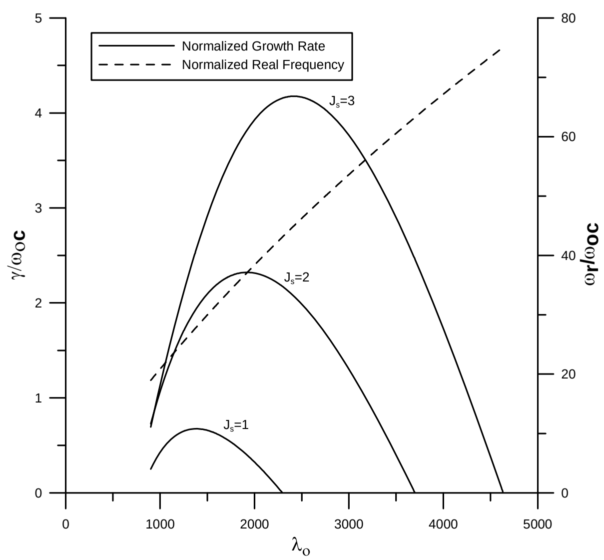

Fig. 1b. Variation of normalized growth rate and real frequency with anisotropic index J (4 - component model). Parameter used here are: n_p/n_e=0.2, n_o/n_e=0.3, n_b/n_e=0.5, ω_{pe}/ω_{ce}=2.0, T_o/T_e=400, T_o/T_b=400, T_o/T_p=20, $k_\parallel/k$=0.09.

During the main phase of the magnetic storm, population of energetic ions increases substantially (Daglis, 1997). Therefore, magnetic storm main phase provides a favorable situation for the excitation of the modes studied here. The occurrence of intense low-frequency (20 - 500 Hz) electrostatic noise bursts at the inner boundary of the proton ring current during the magnetic storm of 16-17th December 1971 has been reported by Anderson and Gurnett (1973). However, relatively less intense waves below 20 Hz have also been observed. They have suggested that this electrostatic noise may be responsible for the pitch angle scattering and loss of ring current protons from the region near the plasmapause boundary during the storm. Further they have suggested a possibility of occurrence of low-frequency noise related to the electrostatic instability described by Coroniti et al. (1972). Recently, Singh et al. (2004) studied the obliquely propagating low-frequency quasi-electrostatic waves ($\omega < \omega_{cp}$) generated by the anisotropic oxygen ions. They found that the growth rate of these excited waves decreases with the increase of the anisotropic index. Also in another study of Singh et al. (2005), the obliquely propagating modes with frequencies near the harmonics of oxygen ion cyclotron frequency were found to become unstable due to pressure anisotropy of the energetic oxygen ions.

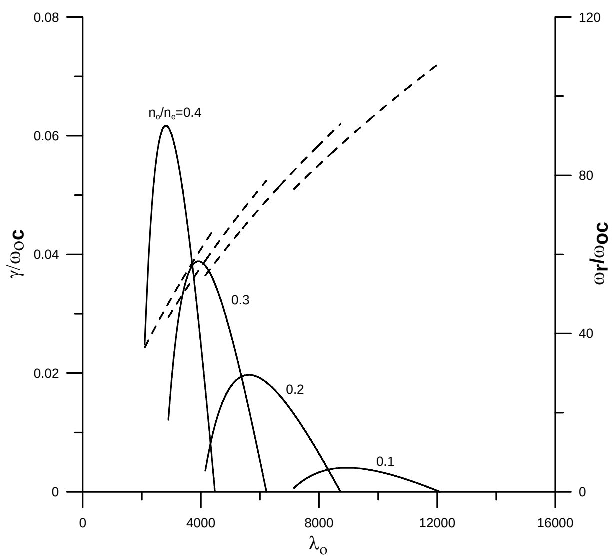

Fig. 2a. Variation of normalized growth rate and real frequency with density ratios (3 - component model). Parameter used here are same as in figure 1a.

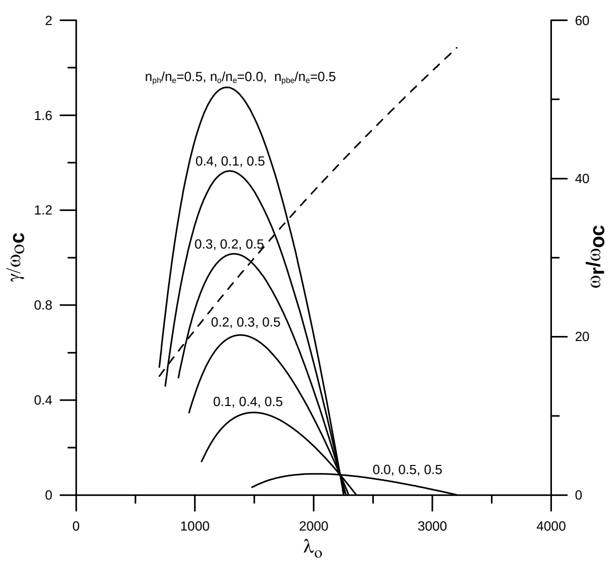

Fig. 2b. Variation of normalized growth rate and real frequency with density ratios (4 - component model). Parameter used here are same as in figure 1b.

During geomagnetic storms the source of free energy for the wave excitation is greatly enhanced due to increased concentration of energetic O^+ ions in the ring current region. Both the temperature anisotropy as well as the loss cone is expected to increase when the energetic O^+ ions are pushed towards lower L-values. These factors lead to the excitation of different kind of waves, including the waves with frequencies greater that the proton cyclotron frequencies in the ring current region during magnetic storm. It is known that, an energetic ions loaded ring current can affect the charge exchange process which is considered as a major process for the ring current decay. The electromagnetic ion cyclotron waves are believed to be important for the wave particle interaction in the ring current region (Thorne and Horne, 1997). The modes studied here can interact with the ring current particles. These interactions can allow efficient energy transfer between different ions under certain conditions which produce large growth rates and high saturation electric field. Further, these excited waves may scatter the ring current particles into the loss cone, leading to their precipitation in the ionosphere. This would contribute to the decay of ring current because of the loss of ring current particles.

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