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A Mechanism for Generation of Ultra Low-frequency Waves in the Polar Cusp Region

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Abstract : Ultra low-frequency (ULF) electromagnetic waves, in the frequency range of ~1 mHz to 3 Hz, have been observed in the polar cusp and other regions of the Earth's magnetosphere by several spacecrafts, e.g., Geotail, Polar and CLUSTER. There are strong indications that these waves are generated locally by the energetic ion beams injected during magnetic reconnection taking place at the magnetopause. Ion beams observed in the polar cusp, plasma sheet boundary layer (PSBL), and on the auroral zone field lines are expected to have spatial gradients in their drift velocity. A generation mechanism for the ULF waves is proposed in terms of kinetic Alfvén wave instability driven by velocity shear of the ion beams. The noise due to velocity shear driven Alfvén modes is electromagnetic in nature, and also has a finite parallel electric field component.

Keywords : Ultra Low-frequency Waves, Polar Cusp Region, kinetic Alfvén, plasma sheet boundary layer (PSBL)

Introduction

In addition to electromagnetic radiation, e.g., visible light, X-rays, ultra-violet (UV) etc., the Sun emits continuously a stream of charged particles called the Solar wind in all directions. The solar wind is a tenuous and highly conducting gas consists mainly of electrons and protons with a little bit of alpha particles and other heavier ions. At the Earth's orbit, the solar wind has density of about 5 particles cm^{-3}, and speeds of ~ 400 km s^{-1}. Both density and velocities are variable, and the speeds can exceed 1500 km s^{-1} during high speed streams. The major part of the geomagnetic field is generated in the earth's outer liquid core by a complex process called Geodynamo which is not fully understood even today. The geomagnetic field, if there were no solar wind, would be a dipole field. The interaction of the solar wind with the geomagnetic fields leads to the formation of the magnetosphere. A 3 dimensional schematic of the Earth's magnetic field is shown in Figure 1.

Ultra-low-frequency (ULF) electromagnetic waves, in ~ (1 mHz -3 Hz) frequency range, have been observed in various regions of the magnetospheric flow boundary, e.g., at the magnetopause, in the plasma sheet boundary layer (PBSL), polar cusp and along the auroral zone (D'Angelo 1973; D'Angelo *et al*., 1977; Gurnett and Frank, 1978, Wygant *et al*., 2002; Nykyri *et al*., 2003; Sundkvist *et al*., 2005; Takada *et al*., 2005; Grison *et al*., 2005). Recent observations of ULF waves by CLUSTER spacecraft in the high altitude polar cusp strongly points towards the waves being generated locally due to sheared plasma flows (Nykyri *et al*., 2003) or ion beams (Sundkvist *et al*., 2005; Grison *et al*., 2005).

An Overview of the cusp crossing of Cluster spacecraft on 23 March 2002 is

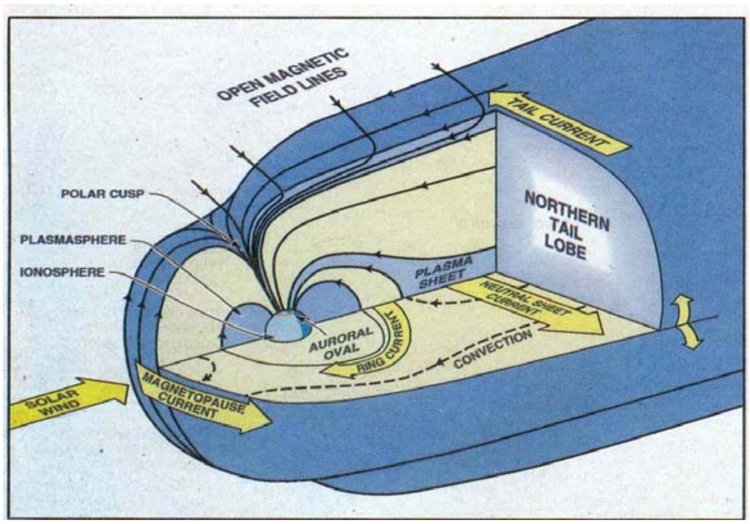

Fig. 1 : shows 3D schematic of the Earth's magnetosphere formed due to the interaction of the solar wind emitted from the Sun (on the left side of the figure) with the geomagnetic field. The ultra-low-frequency (ULF) waves are observed at the magnetopause, in the polar cusp, along the auroral field line and the plasma sheet boundary layer.

shown in Figure 2 (Grison *et al*., 2005). The CLUSTER consists of fleet of 4 spacecraft. At the time of cusp crossing Cluster fleet was in close configuration (~ 100 km of inter-spacecraft separation). Various panels show the background magnetic field, wave and particle data from different experiments on Cluster. Panel (a) shows the DC magnetic field (black curve) and the density (red curve). Panel (b) displays the *äE/äB* ratio (black curve) and the Alfvén velocity, (c) the ion energy spectrogram, (d) the parallel component of the bulk flow velocity (black curve) and the norm of perpendicular component (red curve), (e) shows the power of the magnetic field fluctuations integrated between 1 and 10 Hz, (f) the time frequency spectrogram of these fluctuations, (g) the ion pitch angle spectrogram and (h) the time-frequency spectrogram of electric field fluctuations. Intense low-frequency electromagnetic waves over the range 0.35-2 Hz and higher are seen in Panels (f) and (h) in conjunction with ions beams and flow shear (Panels c, d and g).

Various mechanisms for the generation of ULF waves have been proposed, namely, the Kelvin-Helmholtz (K-H) type instabilities (D'Angelo 1973; Chen and Hasegawa, 1974; D'Angelo *et al*., 1977; Huba, 1981; Lakhina, 1987), the kinetic Alfvén waves driven by flow shears (Hasegawa and Chen, 1976; Mikhailovski and Klimenko, 1980; Lakhina, 1990; Wang *et al*., 1998; Siversky *et al*., 2005). Kinetic Alfvén waves are thought to play an important role in particle acceleration and plasma energization directly due to $E_{\|}$ (parallel electric field) associated with it (Kletzing, 1994; Lysak and Lotko, 1996).

A generation mechanism of ULF waves in terms of kinetic Alfvén waves driven by velocity shear of the ion beam in the polar cusp region has been studied by Lakhina (1990, 2007). Here we discuss a special

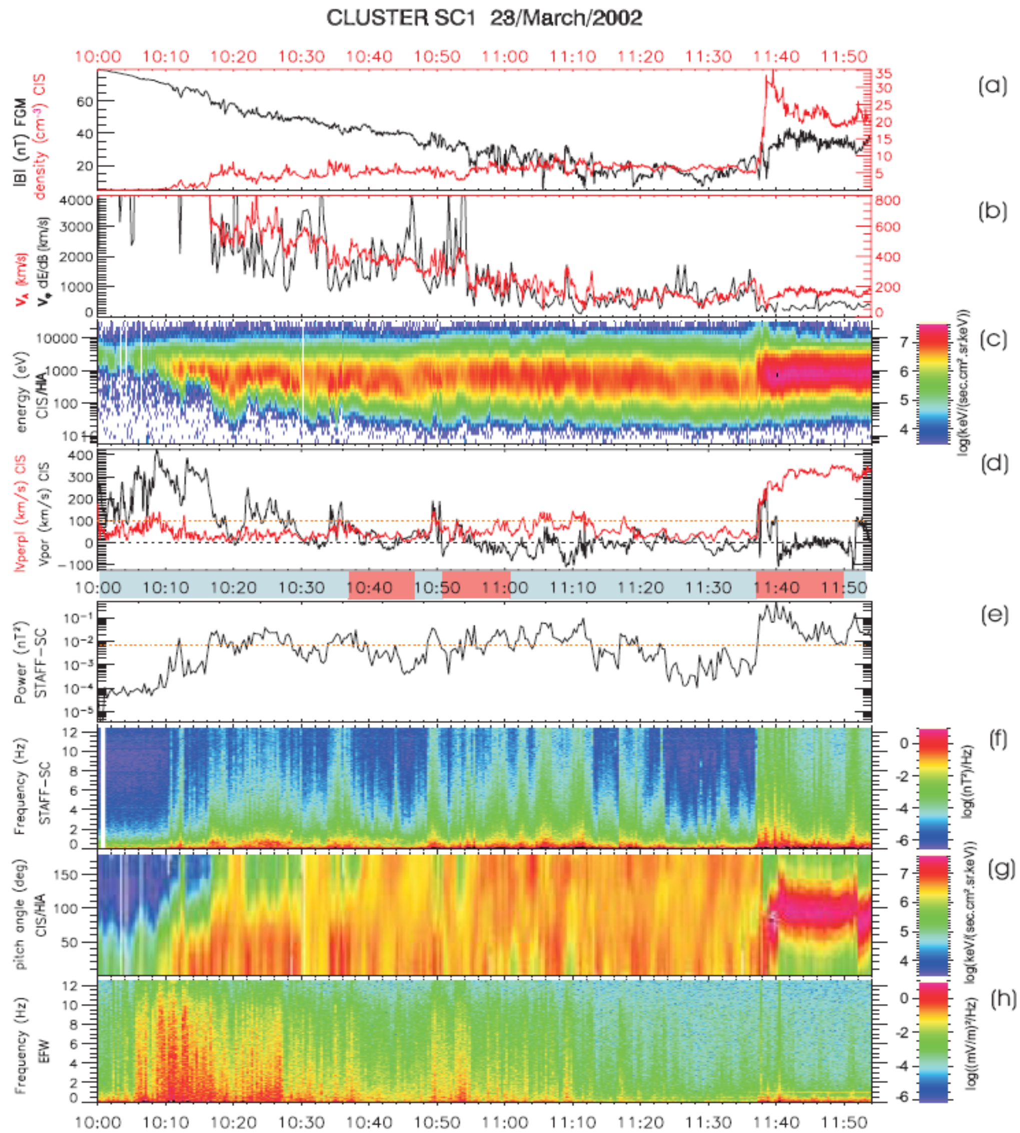

Figure 2 : Overview of the cusp crossing on March 23*rd*, 2002. The data are provided from various instruments onboard spacecraft 1, except EFW whose data are taken from SC4. Panel (a) displays the DC magnetic field given by FGM (black curve) and the density derived from HIA (red curve). Panel (b) displays the *äE/äB* ratio (black curve) and the Alfv´en velocity derived from HIA and FGM data. Panel (c) displays the ion energy spectrogram (HIA), (d) the parallel component of the bulk flow velocity (HIA) (black curve) and the norm of perpendicular component (red curve). Panel (e) shows the power of the magnetic field fluctuations integrated between 1 and 10 Hz (STAFF-SC), (f) the time frequency spectrogram of these fluctuations (STAFF-SC), (g) the ion pitch angle spectrogram (pitch angles are calculated in the spacecraft frame over the [100, 1000] eV energy range) (HIA) and (h) the time-frequency spectrogram of electric field fluctuations (EFW) (taken from Grison *et al*., 2005).

case of Lakhina (2007) model to explain the generation of polar cusp ULF waves in terms of coupled kinetic Alfvén and ion acoustic instability driven by velocity shear of the cold ion beams.

Model for Velocity Shear driven Alfvén Modes

We consider a three component magnetized plasma system, namely, electrons, protons and an ion beam having non-uniform streaming velocity, $\mathbf{V}_B = V_B(x)\,\mathbf{z}$ along the background magnetic field. The subscript j = e, i and B is used for electrons, background ions (protons) and the beam ions, respectively. The densities and temperatures of the plasma species are denoted by N_j and T_j, respectively. In the equilibrium state the charge neutrality condition is obeyed, i.e., $N_e = N_i + N_B$.

The dispersion relation for the low-frequency, i.e., $\omega^2 << \omega^2_{cj}$ (where ω and $\omega_{cj} = (e_j B_0/m_j c)$ are the wave frequency and the cyclotron frequency of the jth species, respectively), and propagating nearly perpendicular to $\mathbf{B}_0$, i.e., $k^2_\perp << k^2_\perp$ ($k_\perp$ and $k_\perp$ are components of the wave vector $\mathbf{k}$ in the directions perpendicular and parallel to the magnetic field $\mathbf{B}_0$, respectively) can be derived from the linearized Vlasov equation and the set of Maxwell equation using the local approximation. The use of local approximation is justified provided $L_V k >> 1$, where k is the wave number and $L_V = V_B(dV_B/dx)^{-1}$ is the velocity gradient scale length. Further, treating the protons and ion beam as cold and the electrons as hot, the dispersion relation can be written as (Lakhina, 1990; 2007)

(1)

where

$$a_0 = \frac{N_i}{N_e} b_i + \frac{N_B}{N_e}\frac{m_i}{m_B}\frac{\omega^2}{\varpi^2} b_B \left(1 - S\frac{k_\perp}{k_{||}}\right), \quad (2)$$

$$a_1 = \frac{N_B}{N_e}\frac{k_\perp^2}{k^2}\frac{\beta_B b_B}{2\lambda_B} S \frac{k_\perp}{k_{||}}, \quad (3)$$

Here $\varpi = (\omega - k_\| V_B)$ is the Doppler shifted frequency, $\omega_{pj} = (4\pi N_j e_j^2/m_j)^{1/2}$ the plasma frequency, and $\alpha_j = (2T_j / m_j)^{1/2}$ the thermal speed of the jth species. Also, $b_j = I_0(\lambda_j)\, e^{-\lambda j}$, where $I_0(\lambda_j)$ is modified Bessel function of order zero with the argument $\lambda_j = (k_\perp^2 \alpha_j^2 / 2\omega_{cj}^2)$, $\hat{a}_j = (8\pi N_e T_j / B_0^2)$ is plasma beta, and $S_B = (1/\omega_{cB}).dV_B/dx$ is the velocity shear.

Equation (1) describes the coupling between the ion acoustic waves and Kinetic Alfvén waves. On putting N_B=0 in (1), the dispersion relation of Hasegawa and Chen (1976) is recovered. For $\hat{a}_i \rightarrow 0$, the coupling between the ion acoustic and kinetic Alfvén wave becomes weak and the two mode decouple, giving the dispersion relation for the kinetic Alfvén wave (Hasegawa and Chen, 1976; Lakhina, 1990) as

$$\omega^2 \approx k_{||}^2 V_A^2 \left[\frac{\lambda_i}{(1 - b_i)} + \frac{T_e}{T_i}\lambda_i\right] \quad (4)$$

which remains unaffected by the velocity shear. On the other hand the, the dispersion relation for the ion-acoustic mode

$$\omega^2 \approx k_{||}^2 c_S^2 a_0 \left[1 + \frac{T_e(1 - b_i)}{T_i}\right]^{-1} \quad (5)$$

is strongly affected by the velocity shear. The ion-acoustic mode can become unstable provided $a_0 < 0$ which requires

$$S > S^* = \frac{k_{||}}{k_{\perp}}[1 + \frac{N_i m_B b_i}{N_B m_i b_B}] \qquad (6)$$

For arbitrary β values and for $\omega > k_{||} V_B$, Eq. (1) gives two roots, one of which is purely growing (i.e., $\gamma > 0$) and the other is a damped modes. Some numerical results for the nonresonant purely growing modes found from the solution of (1) are shown in Figures 3 and 4.

From Figure 3, it is clear that the growth rates increase with an increase in velocity shear (cf. curves 1, 2 and 3) as well as in the ion beam density N_B/N_e (cf. curves 3. 4 and 5). Figure 4 shows that the growth rate first increase and then decrease as $k_{||}/k_{\perp}$ is increased from small to large values (cf. curves 1, 2, 3 and 4). The growth rates are decreased by an increase of $\hat{a}_i$ value.

Discussion and Conclusions

Velocity shear of the ion beams observed in PSBL, Cusp and on auroral field lines can provide the free energy to drive kinetic Alfvén waves. For $\beta_e << 1$, kinetic Alfvén wave and the ion acoustic wave get decoupled. In this case, velocity shear has no effect on the stability of Kinetic Alfvén wave. For higher β_i, i.e., $\beta_i = (m_e/m_i)^{1/2}$ and cold ion beam, kinetic Alfvén waves are coupled with ion-acoustic mode. We consider typical plasma parameters on the auroral/polar cusp field lines at altitudes of 5-7 R_E (D'Angelo et al., 1974; Gurnett and Frank, 1978; Lakhina, 1990): N_B/N_e = (0.01 - 0.2), $V_B/\alpha_B < 2$ and S= (0.5 -1.5). T_B = 1-2 keV, $T_i \sim 10$ eV, and $T_e \sim 100$ eV , and $\omega_{pe}/\omega_{ce} \sim$ (8-20). Then, we have $\beta_i \sim 0.002 – 0.02$. For the above parameters, the couple kinetic Alfvén-acoustic instability driven by cold ion beam occurs for $\lambda_B \sim$ (0.01- 10) with growth rates $|\gamma| \sim (0.01- 0.05)\, \omega_{cB} \sim (0.022 – 0.15)$ Hz. The typical perpendicular wave numbers

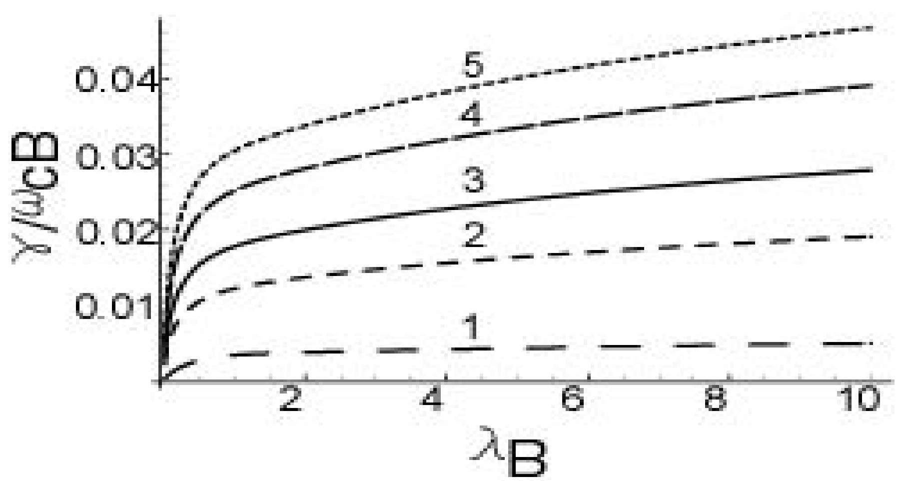

Fig. 3 : Plot of the normalized growth rate versus λ_B for the instability driven by velocity shear of the cold ion beam for $\hat{a}_i$=0.01 and $k_{||}/k_{\perp}$=0.01. For curves, 1, 2 and 3, N_B/N_e=0.1, and S=0.1, 0.5 and 1.0. For curves 4 and 5, S=1.0 and N_B/N_e=0.2 and 0.3.

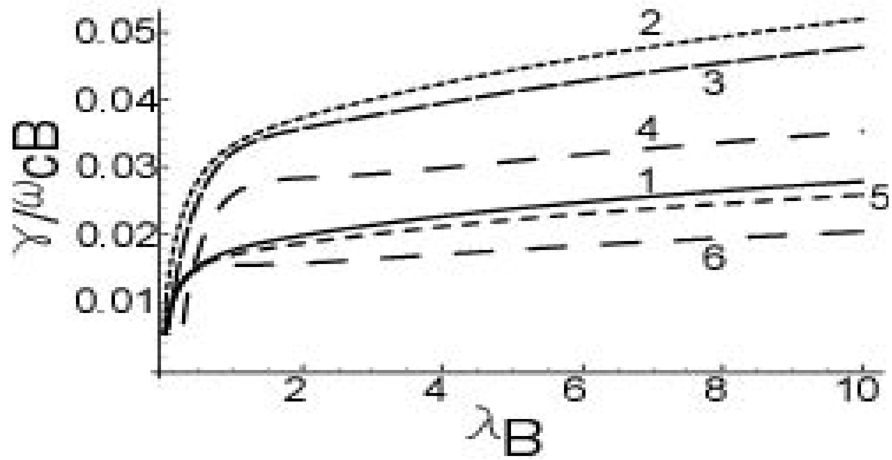

Fig. 4 : Plot of the normalized growth rate versus λ_B for the instability driven by velocity shear of the cold ion beam for N_B/N_e=0.1and S=1.0. For curves, 1, 2, 3 and 4, $\hat{a}_i$=0.01 and $k_{\|}/k\perp$=0.01, 0.05, 0.1 and 0.12. For curves 5 and 6, $k_{\|}/k\perp$=0.01 and $\hat{a}_i$=0.1 and 0.5.

are $k_\perp \sim (0.03\text{-}1.6)\ km^{-1}$, and typical parallel wave numbers $k_{\|} \sim (0.3\ \text{-}12)\times10^{-3}\ km^{-1}$ for $k_{\|}/k_\perp$=0.01. In the moving frame of the satellite, the excited modes would have Doppler shifted frequencies $f' = (\omega \pm k_\perp V_{sat})/2\pi \sim (0 - 800)$ mHz (taking V_{sat}= 3 km s^{-1}). Cold ion beam excited kinetic Alfvén waves modes may be observed at ground as irregular pulsations. Kinetic Alfvén waves driven by ion beam velocity shear would cause precipitation and acceleration of particles. The precipitating particle fluxes would be modulated at the frequency of the Kinetic Alfvén modes. The analysis presented here may explain the generation of some ULF waves observed in the polar cusp by Cluster (Grison et al., 2005) and in PSBL by Geotail (Takada et al 2005).

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