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Abstract

A theoretical description of a possible mechanism to excite Langmuir turbulence in the upstream region of the bow shock is proposed. The mechanism relies on the spatial inhomogeneity of energetic electron streams accelerated at the shock foot and propagating upstream along the magnetic field. The estimation of growth rates and wave amplitudes is in reasonable agreement with the observations. The possibility of the modulational instability is discussed; this results in the excitation of low-frequency density perturbations in the ion-acoustic frequency range. These features have been observed by the AMPTE (Active Magnetospheric Particle Tracer Explorer) spacecraft in the upstream region when the particles are connected by the magnetic field to the shock.

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Introduction

One of the main features of planetary bow shocks is the existence of wave precursors in the form of electrostatic waves in the frequency range of Langmuir waves. These waves were first observed in the upstream region of the earth (Scarf et al., 1971), and subsequently upstream of other planets, eg. Mars (Skalsky et al., 1991) and Venus (Crawford et al., 1990). At the foreshock boundary these waves are accompanied by the appearance of lower frequency ion-acoustic-like turbulence and electromagnetic radiation at the second harmonic of the Langmuir frequency. Usually the excitation mechanism of these waves is connected with the two-stream instability driven by energetic electron beams with $\frac{\partial f}{\partial v_{\parallel}} > 0$. However, detailed measurements of electron distributions obtained by AMPTE-UKS (United Kingdom subsatellite) (Shah et al., 1985) fail to conclusively show the existence of such beams (Nairn et al., 1989). In the absence of waves, electrons with the highest intensities are observed streaming along the magnetic field direction away from the Sun. Intensities for these electrons at energies near 588 eV, for instance, exceed intensities of electrons moving along the field toward the Sun by a factor of about 5. In the presence of the waves, the intensities of both streams at 588 eV are within 10% of each other. The streams from the Sun remain unchanged but the spacecraft is magnetically connected to the bow shock (Bryant et al., 1989) and encounters high intensity electron streams moving towards the Sun from the shock. The correlation of the waves with the high intensity streams from the shock is shown in figure 1. Energetic particles escaping from the bow-shock region are observed in the form of energetic tails with a decreasing velocity distribution function $\left(\frac{\partial f}{\partial v_{\parallel}} \leq 0\right)$. At times when high-frequency electrostatic waves are observed the spacecraft is magnetically connected to the bow shock and enhanced densities of electrons with energies in the range $0.1 - 1keV$ are observed. The correlation of the waves and electrons is illustrated in figure 1, which shows a typical example of AMPTE-UKS data gathered in the upstream region of the earth. If we consider the electrons to form a beam which is difficult to justify we find that the linear analysis indicates that the enhanced densities of the electrons are approximately an order of magnitude below that required to excite the waves (Nairn et al., 1989, Canu et al., 1989). We propose here a new mechanism of wave excitation based on the spatial inhomogeneity of energetic electrons. The inhomogeneity can arise naturally as a result of the finite width of the shock foot region where the electrons are assumed to be accelerated along the field lines by intense lower-hybrid waves or reflected from the shock. An estimation of the spatial growth rates obtained for the conditions present at the earth's bow-shock correspond to distances of the order of several Earth radii Re which is consistent with observations. The estimations of the wave amplitude based on quasi-linear theory are in rough agreement with the observations and give a value of electric field $E \sim 10^{-1} - 1mV/m$ which is sufficient for the development of the modulational instability of Langmuir waves. The threshold for the modulational instability being given by $\frac{\epsilon_o|E|^2}{4n_okT_e} \geq (\Delta k \lambda_{De})^2$ (Vedenov et al., 1967)where

Δk is the modulation wavenumber and λ_{De} is the Debye length. The threshold value of $\frac{\epsilon_o |E|^2}{4 n_o k T_e}$ is of the order of 10^{-5} for the conditions at the bow shock. This instability results in low-frequency ion-acoustic density perturbations, as well as the generation of second harmonic radiation, which is also observed.

Generation of Langmuir waves by inhomogeneous electron streams.

Let us consider the situation of resonant excitation of Langmuir waves by an energetic electron stream which is assumed to be inhomogeneous in the direction perpendicular to the direction of motion of the stream and the magnetic field. We use a kinetic description for the electrons and assume they are unmagnetized since their Larmor radius is large $\frac{k_\perp v_\perp}{\omega_{ce}} \simeq \frac{k_\perp}{k_\parallel} \frac{v_\perp}{v_\parallel} \frac{\omega_{pe}}{\omega_{ce}} > 1$ for the conditions of the earth's bow-shock $\frac{\omega_{pe}}{\omega_{ce}} > 10^2$, $\frac{v_\perp}{v_\parallel} \geq 10^{-1}$. We also assume that oblique propagating waves are excited $k_\perp > k_\parallel$ and $k_\parallel$ is of order $\omega_{pe}/v_\parallel$. The kinetic equation for the perturbation of the distribution function of the energetic electrons in the linear approximation has the following form.

$$\frac{\partial f_1}{\partial t} + v_{ez}\frac{\partial f_1}{\partial z} + v_{e\perp}\cos\varphi\frac{\partial f_1}{\partial x} = \frac{e}{m_e}\left(E_z\frac{\partial f_o}{\partial v_z} + E_x\cos\varphi\frac{\partial f_o}{\partial v_\perp}\right) \quad (1)$$

where we have assumed that z is in the direction of the magnetic field and also that the stream inhomogeneity $\frac{\partial f_1}{\partial x}\frac{1}{f_1}\frac{1}{k_z} \ll 1$, and is perpendicular to z the magnetic field direction, f_o is the equilibrium distribution and f_1, is the perturbation due to the wave.

It is possible to use the perturbation procedure to solve the kinetic equation obtaining the result

$$f_1 = \frac{e}{m_e} \frac{E_z \frac{\partial f_o}{\partial v_z} + E_x \cos\varphi \frac{\partial f_o}{\partial v_\perp}}{i(k_z v_z + k_\perp v_\perp \cos\varphi - \omega)} +$$

$$\frac{e}{m_e} \frac{v_\perp \cos\varphi}{(\underline{k}.\underline{v} - \omega)^2} \frac{\partial}{\partial x} \left[E_z \frac{\partial f_o}{\partial v_z} + E_x \cos\varphi \frac{\partial f_o}{\partial v_\perp} \right] \tag{2}$$

Using Poisson's equation we can obtain the following dispersion relation

$$1 = \frac{\omega_{pe}^2}{\omega^2} + i \frac{\omega_{pe}^2}{2n_o} \int\int \left\{ \frac{k_z}{k^2} \frac{\partial f_o}{\partial v_z} + \frac{(\omega - k_z v_z)}{k^2 v_\perp} \frac{\partial f_o}{\partial v_\perp} \right\} \frac{dv_\perp^2 dv_z}{\sqrt{k_\perp^2 v_\perp^2 - (\omega - k_z v_z)^2}}$$

$$+ i\pi \frac{\omega_{pe}^2}{n_o k^2} \frac{k_y}{k_z} \int dv_\perp^2 \int dv_z \frac{\partial}{\partial x} \left\{ \frac{\frac{\partial f_o}{\partial v_z}}{k_z v_z - \omega} \right\} \tag{3}$$

where we have assumed that $k_\perp v_\perp \ll k_z v_z$ and in that case it is easy to see that the homogeneous term containing $\frac{\partial f_o}{\partial v_z}$ on the right-hand side of equation 3 always results in the damping of the wave for $\frac{\partial f_o}{\partial v_z} < 0$. ie the usual Landau damping condition which goes to zero in the resonant region $v_z \simeq \omega / k_z$. In this case the inhomogeneous term ie the term containing $\frac{\partial}{\partial x}$ derivatives on the right-hand side of equation 3 becomes important and gives rise to growing waves with a growth rate given by the following equation

$$\frac{\gamma}{\omega} = -\frac{\gamma_{LD}}{\omega} + \frac{\pi \omega_{pe}^2}{2n_o k^2} \frac{k_y}{k_z} \frac{\partial}{\partial x} \left[\int dv_\perp^2 \int dv_z \frac{\frac{\partial f_o}{\partial v_z}}{k_z v_z - \omega} \right]. \tag{4}$$

where γ_{LD} is the usual Landau damping rate for the solar wind plasma that stabilizes the excitation of waves with $k\lambda_{De} \geq 0.3 - 0.4$; λ_{De} is the Debye length and we assumed waves to be propagating $\perp$ to the inhomogeniety as usually done in the theory of wave stability analysis in inhomogeneous plasmas (Mikhailovskii et al., 1974) since we assumed the inhomogeniety to be in the x-direction the waves must have a k_y component. Equation (4) demonstrates that there is a threshold for instability dependent on the perpendicular wavenumber k_y and space scale of the inhomogeneity L. An estimation of the growth rate obtained from equation (4) is for $k\lambda_{De} \ll 1$,

$$\frac{\gamma}{\omega} \simeq \frac{1}{2}\frac{n'}{n_o}\frac{\omega_{pe}^2}{k^2(\Delta v_{||})^2}\frac{k_y}{Lk_z^2} \tag{5}$$

where n' is the density of energetic electrons and $\Delta v_{||}$ is the typical spread of their parallel velocity. From observations of the plasma parameters in the upstream region of the bow shock (Vaisberg et al., 1983) we estimate that the inhomogeneity scale length L is of the order 100km, from observations the energetic electron density and velocity are $n' \simeq 10^{-2}n_o - 10^{-3}n_o$, $v_e \simeq 10^9 cm/sec$ and $\Delta v_{||}/v_e \simeq 1$.

For the wavenumbers of excited waves we assume $k_y/k_z \simeq 10$ and $k_z \simeq \omega_{pe}/v_e \sim 10^{-4}cm^{-1}$. From equation (5) we find that the characteristic space scale for exciting the waves is $L \simeq 10v_e/\gamma$ which is of the order $10^4 - 10^5 km$ or $2R_e$ to $20R_e$. This is the distance from the bow shock at which these waves are observed by the spacecraft.

Conclusion

In this paper it has been proposed for the first time that waves generated at the electron plasma frequency upstream of planetary bow shocks may be driven by inhomogenieties in streaming electron populations. The predictions of nonlinear theory are in good agreement with spacecraft observations. In particular the amplitudes are sufficient to drive the modulational instability which generates low frequency density perturbations, also observed simultaneously resulting in wave collapse and caviton formation. The mechanism proposed may have relevance to other space plasma phenomena such as the aurora and solar flares.

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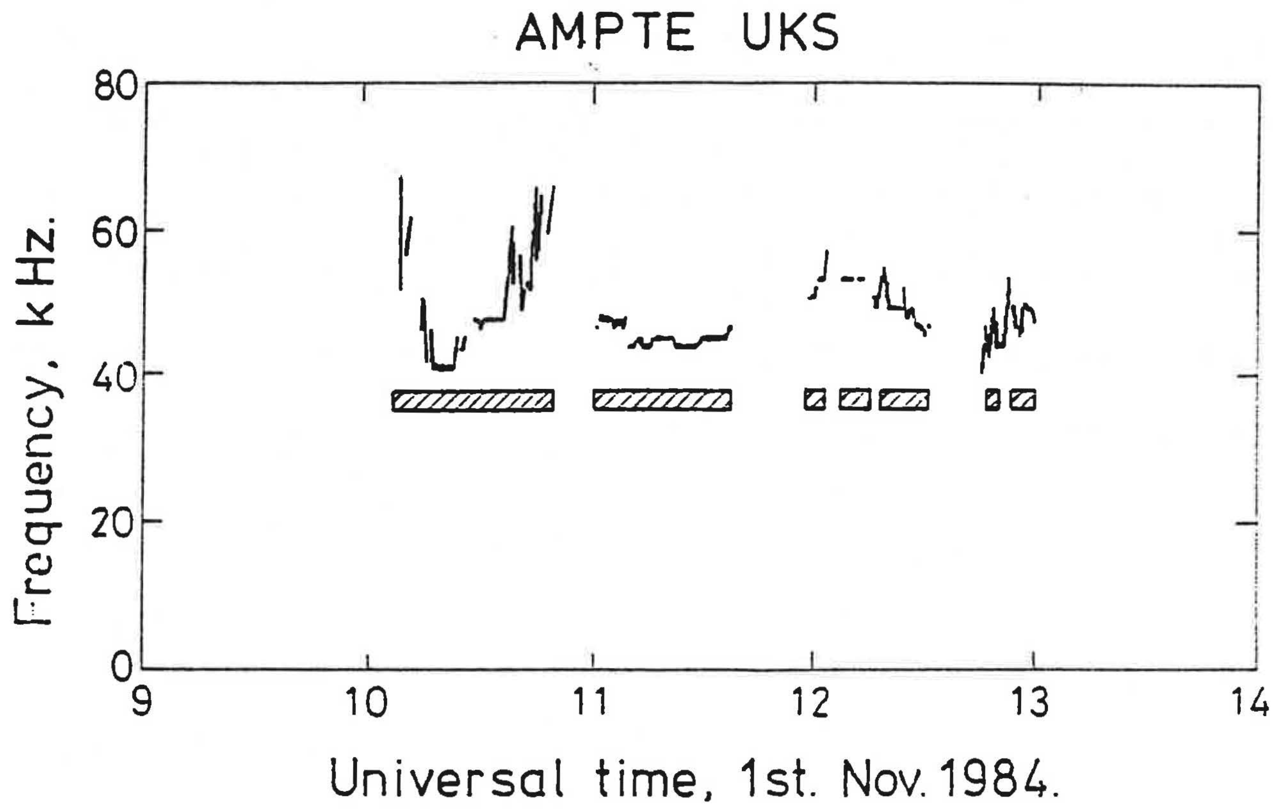
AMPTE UKS
Frequency, kHz.
80
60
40
20
0
9
10
11
12
13
14
Universal time, 1st. Nov. 1984.

Figure 1.

The thin line shows the plasma frequency for times when the amplitude of the waves measured on AMPTE-UKS on 1 November 1984 was significantly above noise levels. The rectangular bars show times when electrons measured on AMPTE-UKS, in the pitch-angle range 0 to 30^o at $588eV \pm 10\%$, had intensities exceeding $5 \times 10^{10} m^{-2} s^{-1} sr^{-1} kev^{-1}$. Electrons at these pitch angles were magnetically connected with the bow shock only at the times when these high intensities were observed. (Wave measurements courtesy of L J C Woolliscroft)