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Generation of Electron Plasma Waves in the Upstream Solar Wind

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Electron plasma waves with amplitudes as high as 10 mV/m have been measured in the electron foreshock region of the earth's bow shock. It is shown that a population of stable suprathermal electrons of the type observed can produce the measured level of enhanced fluctuations without becoming unstable. The steady state wave level is given by the balancing between emission and absorption. The apparent association of fluctuation enhancements with sharp changes in electron fluxes can be understood in terms of modification of the electron distribution due to acceleration processes. The expected $2\omega_{pe}$ radiation from the model is consistent with the observations.

INTRODUCTION

Recent observations made by the ISEE 1 and 2 satellites in the upstream region of the earth's bow shock have confirmed the association of electron plasma waves with enhancements of energetic electrons [*Parks et al.*, 1981; *Harvey et al.*, 1981; *Anderson et al.*, 1981]. These measurements are very similar to previous observations made by the OGO 5 and IMP 6 satellites [*Scarf et al.*, 1971; *Filbert and Kellogg*, 1979]. The electric field fluctuations associated with the plasma waves are nearly monochromatic in frequency ($\sim \omega_{pe}$). They correlate well with the enhancement in fluxes of energetic electrons of 1–2 keV and terminate abruptly when the flux enhancements stop. The level of fluctuations varies between ten's of micro-volts per meter to 1 mV/m, with an occasional peak of $\sim$ 10 mV/m; enhancements are associated with increases or decreases in the energetic electron flux. Furthermore, since the observed wave level, as measured by ISEE 1 and 2 using different antenna lengths, is the same, we can conclude that the electric field fluctuations have long wavelengths ($\lambda > 215$m).

Beam-plasma (bump on tail) or two-stream instability has been proposed as a generation mechanism for these fluctuations [*Fredricks and Scarf*, 1971; *Filbert and Kellogg*, 1979; *Anderson et al.*, 1981]. This mechanism requires the presence of a directional beam of energetic electrons streaming through a background plasma [*Krall and Trivelpiece*, 1973]. However, there seems to be no conclusive evidence indicating the presence of such a beam [*Feldman et al.*, 1973; *Filbert and Kellogg*, 1979; *Anderson et al.*, 1981]. On the large scale, the electron distribution in the foreshock region appears isotropic.

In this paper we examine a situation analogous to critical fluctuation, the phenomenon in which the level of collective mode increases dramatically as the damping rate becomes vanishingly small [*Ichimaru*, 1973]. We demonstrate that by adopting a plausible model of electron distribution similar to the type observed, the measured level of electric field fluctuation at the local plasma frequency ω_{pe} can be generated. We will also show that the expected level of $2\omega_{pe}$ emission agrees with the ISEE 3 observations [*Hoang et al.*, 1981].

ELECTROSTATIC FLUCTUATIONS AT ω_{pe}

In this section, we calculate the spectrum and the average amplitude of the plasma fluctuations at the fundamental harmonic of the electron plasma frequency ω_{pe}. Standard treatment of the theory on electric field fluctuations in a plasma can be found in general texts on plasma physics [*Ichimaru*, 1973; *Krall and Trivelpiece*, 1973]. The energy density of the fluctuating electric field is proportional to

$$\delta E^2(\omega_{pe}) = -\frac{m_e\omega_{pe}}{(2\pi)^3}\int d\mathbf{k}\,\frac{\int d\mathbf{v}\;\delta(\omega_{pe}-\mathbf{k}\cdot\mathbf{v})\,f(\mathbf{v})}{\int d\mathbf{v}\;\delta(\omega_{pe}-\mathbf{k}\cdot\mathbf{v})\,\mathbf{k}\cdot\partial f(\mathbf{v})/\partial\mathbf{v}} \tag{1}$$

For an isotropic distribution, $f(\mathbf{v}) = f(v)$, we can write

$$\delta E^2(\omega_{pe}) = \frac{4\pi m_e\omega_{pe}{}^3}{(2\pi)^3}\int_{u_0}^{\infty}\frac{du}{u^4}\,\frac{\int_u^{\infty} dv\; v\,f(v)}{f(u)} \tag{2}$$

The lower limit of integration u_0 is chosen to be three times the thermal velocity of the thermal background plasma ($T \sim$ 10 eV), so that Landau damping is negligible.

Consider a model isotropic distribution composed of a thermal background with thermal velocity $v_e = (2T_e/m_e)^{1/2}$, and an energetic component which has a streaming velocity v_0 and exists mainly for $v \geq \alpha v_0$. This energetic population may also have a spread $v_{\rm H}$ in velocity space. Such distribution is precisely the gap distribution described by *Tidman and Dupree* [1965] and *Melrose* [1975], which can be represented by

$$f(v) = \frac{\beta}{\pi^{3/2}v_e{}^3}\exp\left[-\frac{v^2}{v_e{}^2}\right] + \frac{(1-\beta)}{A}(v-\alpha v_0)^2 \cdot \exp\left[-\frac{(v-v_0)^2}{v_{\rm H}{}^2}\right] \tag{3}$$

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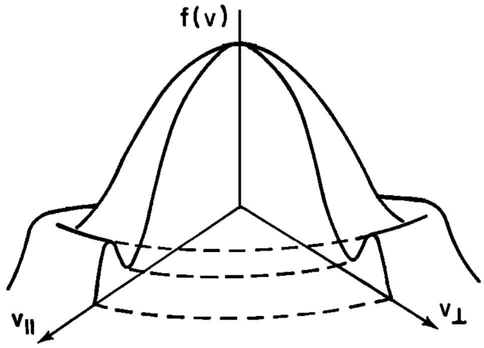

Fig. 1a

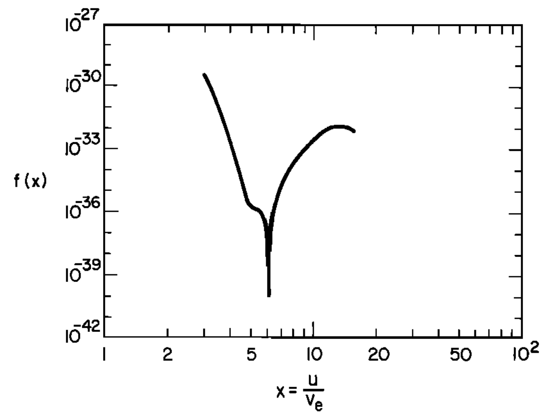

Fig. 1b

Fig. 1. (*a*) Sketch of the model isotropic gap distribution. (*b*) Plot of the model distribution function given by equation (3) for $n_0 = 10\ \text{cm}^{-3}$, $T \simeq 10$ eV, $\delta = 10^{-3}$, $T_0 = 1.5$ keV, $T_H = 100$ eV.

where $|1 - \beta| \ll 1$, α is a prescribed parameter between zero and unity, and A is a normalization constant such that $\int f(\mathbf{v})\, d\mathbf{v} \equiv 1$ (see Figures 1*a* and 1*b*); we then have

$$A = \pi^{3/2} v_H^3 \left\{ \left[\left[\frac{3}{2} v_H^2 + (5 - 4\alpha) v_0^2 + (1 - \alpha)^2 v_0^2 \right] \right. \right.$$

$$\left. \cdot \left[1 + \operatorname{erf}\left(\frac{v_0}{v_H} \right) \right] + \frac{2(1 - \alpha)^2 v_0^4}{v_H^2} \operatorname{erf}\left(\frac{v_0}{v_H} \right) \right\}$$

$$+ 2\pi^{3/2} (1 - \alpha)^2 v_0^4 v_H + [(5 - 4\alpha) v_0 v_H^4 + 2\pi (1 - \alpha)^2 v_0^3 v_H^2]$$

$$\cdot \exp\left(- \frac{v_0^2}{v_H^2} \right)$$

By substituting (3) into (2) we obtain

$$\delta E^2(\omega_{pe}) = \frac{4\pi m_e \omega_{pe}^3}{(2\pi)^3} \int_{u_0}^{\infty} \frac{du}{u^4} \frac{G(u)}{f(u)} \qquad (4)$$

where

$$G(u) = \frac{1}{2\pi^{3/2} v_e} \exp\left[- \frac{u^2}{v_e^2} \right] + \frac{\delta}{A} I(u)$$

with $\delta = (1 - \beta)/\beta$ and

$$I(u) = \left[\frac{\sqrt{\pi}(3 - 2\alpha) v_0 v_H^3}{4} + \frac{(1 - \alpha)^2 \sqrt{\pi} v_0^3 v_H}{2} \right]$$

$$\cdot \left[1 + \operatorname{erf}\left(\frac{v_0 - u}{v_H} \right) \right]$$

$$+ \frac{v_H^2}{2} [(u - v_0)^2 + (3 - 2\alpha) v_0 (u - v_0)$$

$$+ v_H^2 + (1 - \alpha)(3 - \alpha) v_0^2] \exp\left[- \frac{(u - v_0)^2}{v_H^2} \right]$$

Equation (4) is equivalent to equation (3.15) of *Papadopoulos and Freund* [1979]. The physical interpretation of (4) is that of the Kirchoff's law, i.e., emission is balanced by absorption in steady state even for plasmas not in thermal equilibrium. $G(u)$ represents the emission of waves with phase velocity u; and $f(u)$ is proportional to the damping rate. In the gap region, $v_e \ll u < v_0$, the emission is predominantly due to the energetic electrons, that is, $G(u) \simeq (\delta/A)I(u)$. However, the damping rate ($\sim f(u)$) is vanishingly small, which results in a significantly enhanced fluctuation level. We present below the results of integrating numerically (4), for typical parameters.

NUMERICAL RESULTS

We have adopted typical values for the background density $n_0 \simeq 10\ \text{cm}^{-3}$ and temperature $T \simeq 10$ eV for the foreshock region and have assumed $\delta = 10^{-3}$ and $\alpha = 0.5$ for our calculations. Figures 2*a*, 2*b*, and 2*c* plot the amplitude of the fluctuating electric field as a function of the average velocity of the energetic electrons for various values of T_H (100 eV, 500 eV, 2 keV), the temperature of the energetic component. The dependence of the amplitude on the thermal spread of the energetic electrons is rather weak, except at low energies ($v_0 \gtrsim 3v_e$) where the fluctuation level is small ($\delta E \sim 10^{-3}$mV/m). As the fast electrons become more and more energetic, the gap in the distribution function widens. Waves generated by the energetic electrons suffer less absorption or damping by the thermal background. The amplitude reaches the level of 1 mV/m at $v_0 \simeq 12.5 v_e$. This corresponds to an energy of 1.56 keV for the fast electrons.

Anderson et al. [1981] indicated that, typically, $T_H \sim 100$ eV and electron flux enhancements occur at energies above 200 eV. It is more interesting to note that frequent bursting enhancements occur at about 1.5 keV, lasting from a few seconds to a few minutes [*Parks et al.*, 1981]. Our choice of $\alpha = 0.5$ and $T_0 = 1.5$ keV corresponds to a lower cutoff energy of 375 eV for the energetic electrons. This is well above the observed cutoff energy for electron enhancement. The frequently observed bursts of electrons at around 1.5 keV are, therefore, the likely candidates that cause the 1-mV/m fluctuation level. Enhancement of electron fluxes at 1.8–2 keV can also account for the occasional electric field amplitude of the order of 10 mV/m (Figure 2*a*).

Enhanced fluctuation associated with sharp increases or decreases in the electron flux can also be understood within the framework of our model. The computed level of electric field fluctuation depends rather weakly on δ, the energetic to background electron density ratio. The fluctuation level is determined mainly by two parameters: v_0 (Figures 2) and α (equation (4)). These characterize the width of the gap region and the ascending slope of the energetic component in the distribution function. For a given v_0, the amplitude of the fluctuating electric field becomes a function of α. An increase of the flux of electrons with velocities around v_0 could be due to the acceleration of lower energy electrons. This flux increase of energetic electrons at v_0 causes the gap to widen and deepen. Thus, a larger α is prescribed, which in turn leads to an increase of the fluctuation level (see equation (4)). Similarly, a decrease of electron flux around v_0 could mean further acceleration of electrons. These acceleration processes generally shift v_0 to higher velocities. The widening of the gap subjects waves to less damping by the background electrons, resulting in an apparent enhanced level of fluctuation.

Figures 3 and 4 show the spectral power of the fluctuation for T_H = 100 eV and T_0 = 1.5 keV. We see that the fluctuation is highly monochromatic. In Figure 4, we notice that the spectrum peaks at $\omega/\omega_e \simeq 1.035$ which, when substituted into the dispersion relation for electron plasma waves, gives the wavelengths of fluctuations $\lambda \simeq 283$ m (substantially longer than 215 m).

Hoang et al. [1981] recently reported their ISEE 3 observations of the $2\omega_{pe}$ radio radiation from the upstream region of the bow shock. The observed flux density in W m^{-2} Hz^{-1} is of the order of 2×10^{-21} at 80 kHz to 10^{-20} at 110 kHz; and the bandwidth varies between 3 kHz and 20 kHz. We can then compare the observed fluxes to that which is expected from the model. As our model distribution is isotropic, plasma waves are generated in all directions. Oppositely directed electrostatic plasma oscillations can

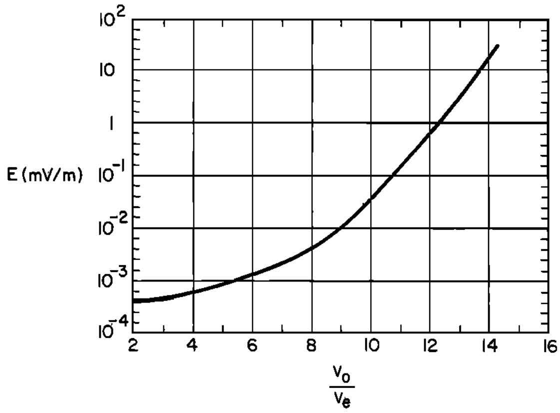

Fig. 2*a*

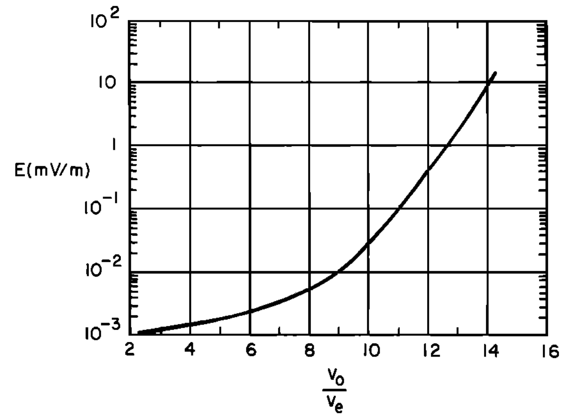

Fig. 2*b*

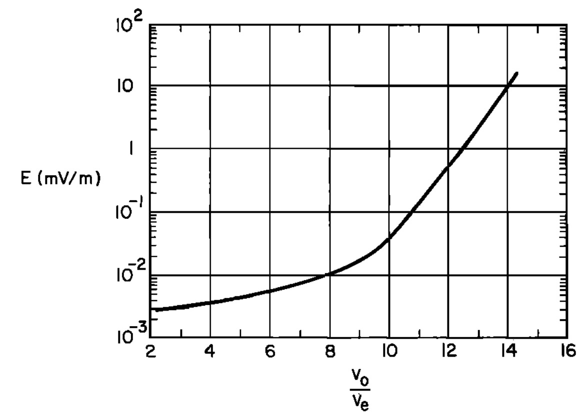

Fig. 2*c*

Fig. 2. (*a*) Plot of E(mV/m) versus v_0/v_e for T_H = 100 eV. (*b*) Plot of E(mV/m) versus v_0/v_e for T_H = 500 eV. (*c*) Plot of E(mV/m) versus v_0/v_e for T_H = 2 keV.

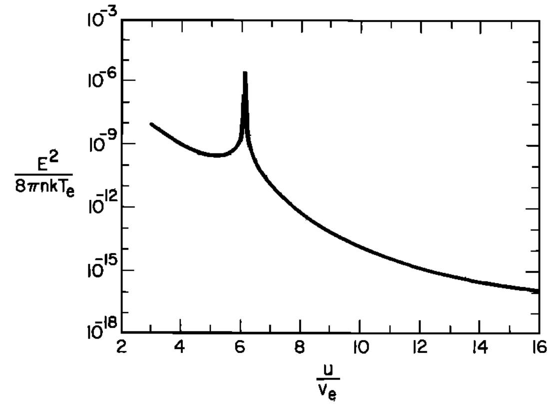

Fig. 3. Calculated energy spectrum of the fluctuations as a function of the phase velocity.

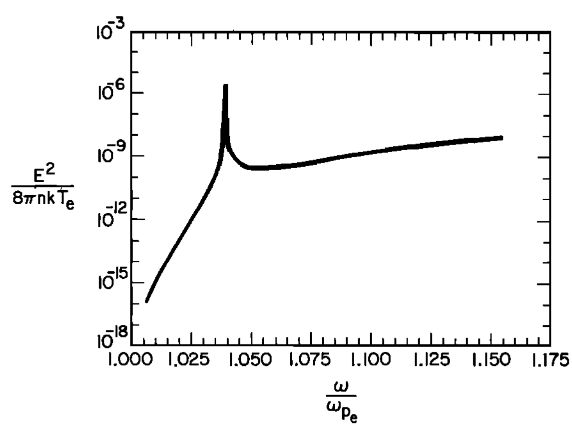

Fig. 4. Calculated energy spectrum of the fluctuations as a function of frequency.

collide to produce electromagnetic radiation at $2\omega_{pe}$. The emissivity (in erg cm^{-3} s^{-1}) is given by *Tidman and Dupree* [1965] as well as *Papadopoulos and Freund* [1979]; i.e.,

$$J(2\omega_{pe}) = \frac{2\sqrt{3}\, e^2 \omega_{pe}{}^4}{5\pi^2 c^5} \int_0^{k_{De}} dk \frac{Fe^2\left(\frac{\omega_{pe}}{k}\right)}{\left|Fe'\left(\frac{\omega_{pe}}{k}\right)\right|^2} \tag{5}$$

where $Fe(u) = \int d\mathbf{v}\ \delta(u - \mathbf{k} \cdot \mathbf{v}/|\mathbf{k}|) f(\mathbf{v})$ is the reduced distribution function, and k_{De} is the Debye wave number. By substituting our model distribution in (3) into (5) and using parameters that are appropriate for generating a fluctuation level of ~ 1 mV/m (i.e., n_0 = 10 cm^{-3}, T = 10 eV, $\delta = 10^{-3}$, T_0 = 1.5 keV, T_H = 100 eV, and α = 0.5), we obtained that $J(2\omega_{pe}) \sim 7 \times 10^{-23}$ W m^{-3}. The corresponding flux density at the observation point is simply given by

$$F(2\omega_{pe}) \simeq \frac{JL^3}{D^2 \Delta f} \tag{6}$$

where L is a typical source dimension, D is the distance between the observation point and the source region, and Δf is the bandwidth of the radiation. We can see from Figure 1 of *Hoang et al.* [1981] that $L \sim 10\ R_E$ and $D \sim 200\ R_E$. Taking an average bandwidth $\Delta f \sim 10$ kHz, (6) gives $F(2\omega_{pe}) \simeq 1.1 \times 10^{-21}$ W m^{-2} Hz^{-1}. This is entirely consistent with the observations.

SUMMARY AND DISCUSSION

We have examined above numerically the possibility that the electrostatic waves observed near ω_{pe} in the electron foreshock are due to enhanced bremsstrahlung produced by the energetic electron component rather than an instability. Since the observed distributions are rather dynamic, we attempted to investigate the sensitivity of the expected wave levels to various parameters that model a gap type suprathermal distribution, such as was observed by *Anderson et al.* (e.g., see their Figure 14). It was found that wave energy levels of the order of 10^{-3} mV/m are consistent with the inherent fluctuations of a nonthermal plasma, while being rather insensitive to the number density of the energetic electrons and their associated thermal spread. Enhanced levels of 1–10 mV/m can be accounted for by an increase in the flux of 1.5–2 keV electrons, while remaining stable. The results are sensitive to the existence of a gap, but not critically dependent on its details. Our assumption of isotropy was made for computational simplicity and the presence of any stable anisotropies does not affect the results by more than a few percent. In conclusion, we feel that our results indicate that enhanced bremsstrahlung can account for even the highest observed levels of electron plasma waves in the electron foreshock, if the energetic electron component approaches the region of marginal stability from below (i.e., it simply approaches instability without ever reaching the limit of stimulated growth). An examination of the consequences of this fact with respect to the operating acceleration processes [*Papadopoulos,* 1981] is presently under study.

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