

Turbulent expansion during parametric plasma heating

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The anomalously long lifetime of the stimulated electromagnetic emission observed after the pump wave is turned off in experiments on the parametric heating of the ionosphere is explained in terms of a turbulent expansion of a cloud of superthermal particles in a collisionless plasma.

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During parametric heating of a plasma, a significant fraction of the pump energy is expended on accelerating electrons to superthermal velocities^{1,2}; these electrons increase the thermal conductivity dramatically and oppose the buildup of a high concentration of energy in the plasma. At certain power levels, however, this thermal conductivity can be substantially suppressed: If the energy of the plasma turbulence is high enough, the superthermal electrons undergo a Brownian motion because of scattering by plasma waves, and the expansion of these electrons becomes diffusive with an expansion velocity much lower than the velocity of an individual particle. After the pump wave is turned off, an induction effect occurs, as the turbulence level is maintained for a time by the superthermal electrons which have accumulated in a layer in the course of the acceleration, and the expansion of the superthermal particles remains turbulent in nature.

Recent experiments on the parametric heating of the ionosphere confirm this interpretation, in our opinion. The application of intense electromagnetic radiation in the short-wave range to the ionospheric *F* layer has been accompanied by a comparatively broad-band stimulated radio emission with a central frequency *f* near the frequency of the pump wave^{3,4} ($f = f_0 \pm \Delta f, \Delta f/f \sim 0.02$). This emission apparently results from the conversion of plasma waves into electromagnetic radiation in a three-wave interaction with ion sound.³ Superthermal electrons accelerated to $W \sim 25$ – 30 eV have been observed simultaneously.⁵

Surprisingly, the stimulated emission is observed even after the pump wave is turned off, for a time $\Delta\tau \sim 0.1 s \gg \nu^{-1} \sim 3 \times 10^{-3} s$, where the reciprocal of the electron collision rate, ν^{-1} , is a measure of the lifetime of the plasma waves. This persistence of the stimulated emission can be explained on the basis of these induction effects accompanying the turbulent expansion of superthermal electrons. These effects can be described quantitatively by the turbulent-expansion equations derived in Ref. 6. In simplified form, these equations are

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial s} \frac{1}{D + D_0} \frac{\partial n}{\partial s} + q, \quad (1)$$

$$\frac{\partial D}{\partial t} = -(\nu + \alpha n) D + \beta \left| \frac{\partial n}{\partial s} \right|, \quad (2)$$

where n is the number of superthermal particles, s is the coordinate along which the expansion occurs, D_0 is determined by the parametric turbulence level, D is the intensity of the plasma waves which are excited during the expansion of the superthermal electrons ($D_0 = 12\pi^3 e^2 E_0 / m^2 v_0^5 k_0$, where v_0 is the average velocity of the superthermal electrons, k_0 is a characteristic wave number in the plasma-wave spectrum, and E_0 is the energy density of the parametrically excited plasma waves per unit volume), and D is given by a similar expression. The coefficients α and β are

$$\alpha = \frac{3\omega_p}{4n_p\pi} \left(\frac{v_{ph}}{v_0} \right)^3, \quad \beta \approx 0.3 \frac{v_{ph}^2}{v_0^3} \frac{\omega_p}{n_p}, \quad (3)$$

where v_{ph} is the minimum phase velocity of the waves, n_p is the density of the background plasma, and $\omega_p = (4\pi e^2 n_p / m)^{1/2}$ is the electron plasma frequency. Equations (1)–(3) are written under the assumption that the electrons are essentially accelerated only up to the ionization energy W_0 , and the primary effect is the accumulation in the interaction volume of superthermal electrons with energies $\sim W_0$. The source q describes the secondary electrons which result from the ionization.

From the steady-state solution of system (1)–(2) we see a buildup of superthermal electrons in a narrow layer of thickness $2s_0$, in which a parametric instability occurs. After the pump wave is turned off ($D_0 = q = 0$), the following events occur: The $n(s)$ profile becomes deformed into a step, and the plasma waves concentrate at the front of the expanding cloud of superthermal electrons. If we ignore transients over time intervals $\Delta\tau \leq \nu^{-1}$, then we can ignore the derivative $\partial D / \partial t$ in (2). In this approximation, the solution of (1)–(2) is

$$n = n_m(t) 1(s_{ph} - s), \quad D = D_m(t) \delta(s - s_{ph}),$$

$$s_{ph} = s_0 + ut, \quad D_m = \frac{\beta n_m}{\alpha n_m + \nu}, \quad (4)$$

$$n_m = \frac{n_{m0} s_0}{s_0 + ut}, \quad u = \alpha / \beta \approx v_{ph}$$

After the pump is turned off, the temporal characteristics are thus determined by the three parameters n_{m0} , s_0 , and v_{ph} . The minimum phase velocity of the plasma waves satisfies $v_{ph} \geq 3v_{Te}$, where v_{Te} is the thermal velocity of the electrons of the background plasma. A maximum value of n_{m0} is set by the threshold for the parametric instability: $n_{m0} = \alpha^{-1} \nu \delta$, where δ , the extent to which the threshold is exceeded, lies in the range ~ 1 – 10 in actual experiments. Setting $v_{Te} \sim 2 \times 10^7$ cm/s, $\delta \sim 3$, $\nu \sim 3 \times 10^2$ s $^{-1}$, and $s_0 \sim 2$ km, we find that D_m decreases by an order of magnitude over a characteristic time $\tau_0 \sim (\nu \delta - 1) s_0 / v_{ph} \sim 0.1$ s, in fair agreement with experiment. To estimate the width of the wave spectrum, we work from the dispersion relation for the plasma waves: $(\Delta f / f) \approx (f_H^2 / 2f^2) \Delta(\sin^2 \theta) + (3/2)(k_0 v_{Te}^2 / \omega^2) \Delta k$, where f_H is the electron gyrofrequency, $\omega = 2\pi f$, and $\theta = (\mathbf{k} \hat{\mathbf{H}})$. In the model of Ref. 6 we have $\Delta k \rightarrow 0$ and $\Delta \theta \sim 1$. We thus find $\Delta f / f \sim f_H^2 / 2f^2$, and under the conditions prevailing in the ionosphere we would have $\Delta f / f \sim 0.03$, in approximate agreement with the observed value.

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