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Low-Frequency Radio Emissions in the Outer Heliosphere: Constraints on Emission Processes

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Low-frequency radio emissions at 2 and 3 kHz were observed by the plasma wave receivers on both Voyager 1 and Voyager 2 during the interval 1983–1987 at radial distances from the Sun greater than 17 AU and 13 AU, respectively. We present a report on progress toward a model in which the emitted radio waves are generated near multiples of the plasma frequency f_p by nonlinear processes involving electrostatic Langmuir waves at a source in the outer heliosphere. Constraints on the emission processes and source characteristics are discussed. The observed spectral flux density of $\sim 10^{-17}$ W m^{-2} Hz^{-1} corresponds to an inferred minimum brightness temperature of $\sim 10^{15}$ K, comparable to the most intense type III solar radio bursts and more intense than the $2f_p$ radiation generated at the Earth's bow shock. Minimum Langmuir wave electric fields in the source region, based on the kinematics of the radiation processes at $2f_p$, lie in the range $\sim$3–30 μV/m for nominal source and electron beam parameters. This field strength is plausible based on the intensity of Langmuir waves observed upstream of planetary bow shocks in the solar wind.

INTRODUCTION

The interaction between the outstreaming supersonic solar wind plasma and the ambient ionized component of the very local interstellar medium is widely believed to result in the formation of an inner heliospheric shock, heliopause, and possibly an outer bow shock system [e.g., *Axford*, 1973; *Baranov et al.*, 1979; *Fahr et al.*, 1986; *Baranov*, 1990; *Suess*, 1990]. Locating the heliospheric boundaries is a major objective of the Voyager mission, now that the planetary observation phase is completed. The Voyager 1 and 2 and Pioneer 11 spacecraft are moving toward the front side of these boundaries at various radial distances r (from the Sun), heliospheric latitudes δ, and longitudes φ. Discussion of the plasma waves expected near these heliospheric boundaries is therefore of considerable interest. Moreover, during the interval 1983–1987, Voyager 1 and Voyager 2, at $r \gtrsim 17$ AU and 13 AU, respectively, observed radio emissions [*Kurth et al.*, 1984, 1986, 1987; *Kurth*, 1990*a*, *b*] at low frequencies $f \sim 2$ and 3 kHz. These emissions are above the local electron plasma frequency f_p [*Kurth*, 1990*b*] and show an upward drift in frequency at a rate of $\sim$1 kHz/yr [*Kurth et al.*, 1987; *Czechowski and Grzedzielski*, 1990]. Possible sources for the low-frequency radio emissions include electromagnetic radiation generated at multiples of f_p near from either the inner heliospheric shock [*Kurth et al.*, 1984, 1987] or the heliopause [*Fahr et al.*, 1986]. Both of these interpretations for the radio emissions and also the deep space observations of the anomalous decrease with radial distance of the Ly α glow [*Judge et al.*, 1990] suggest the presence of a nearby solar wind shock in the outer regions of the heliosphere.

Radiation near multiples of f_p has been observed in type II and III solar radio bursts [e.g., *Melrose*, 1980*a*, *b*; *McLean and Labrum*, 1985], upstream of the terrestrial bow shock [*Dunckel*, 1974; *Gurnett*, 1975; *Hoang et al.*, 1981; *Cairns*, 1986; *Lacombe et al.*, 1988], near some interplanetary shocks [*Kurth et al.*, 1981], and in laboratory plasmas [e.g., *Benford et al.*, 1980]. Essentially all theories for such radiation involve nonlinear processes with electrostatic (longitudinal) electron plasma oscillations, called Langmuir waves. Langmuir waves are produced by a beam-plasma instability, along magnetic field lines that are nearly tangential to the shock surface. The oscillation frequency of Langmuir waves is very close to the local plasma frequency f_p, which is directly related to the local electron plasma density: $f_p \approx 9$ kHz $n_e^{1/2}$ (cm^{-3}).

In another paper [*Macek et al.*, 1991] we presented a simple analytic model for the generation mechanism of Langmuir waves sunward of the inner heliospheric shock. The model is directly analogous to the accepted models for the generation of plasma oscillations upstream of the Earth's bow shock. It involves electrons reflected or leaking from a region of the shock. A minimum velocity, termed the cutoff velocity, is required to escape sunward of the shock. This characteristic velocity results in an electron distribution which is unstable to the growth of the Langmuir waves.

Various mechanisms for converting Langmuir waves into the electromagnetic radiation at multiples of f_p have been considered [*Ginzburg and Zheleznyakov*, 1958; *Melrose*, 1980*a*, *b*; *McLean and Labrum*, 1985; *Cairns*, 1988]. In this paper we place constraints on the characteristics of the emission processes and source regions capable of generating radiation at multiples of f_p and compare these constraints with the intensity of the observed 2- to 3-kHz radio emission in the outer heliosphere.

Our first step is to calculate the brightness temperature and range of volume emissivity for the observed radiation. These values are then compared with the characteristics of known radiation at multiples of f_p. The derived brightness temperatures are then used to constrain the source of the Langmuir waves and rule out certain emission mechanisms for the radiation. Minimum values for the Langmuir wave electric field intensity are derived and compared with observed values at planetary bow shocks. Path lengths re-

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quired for the radiation to reach the observed levels are then derived and discussed. We suggest a simple source model for the waves and compare our calculated constraints with this model. Lastly, the relevance of these ideas to possible direct observations of the heliospheric boundaries, which is a major objective of the Voyager Interstellar Mission, is discussed.

OBSERVATIONAL CONSTRAINTS

We use a semiclassical formalism [*Melrose*, 1980*a*] in which waves of any mode σ with wave vectors $\mathbf{k}^\sigma$ are regarded as a collection of wave quanta. The total energy density W^σ is related to the spectral energy density, or effective wave temperature $T^\sigma(\mathbf{k})$, i.e., the energy density per an elemental range $d^3\mathbf{k}^\sigma/(2\pi)^3$ in phase space (taken in units of the Boltzmann's constant κ), by $W^\sigma = \int \kappa T^\sigma(\mathbf{k})\, d^3\mathbf{k}^\sigma/(2\pi)^3$. Transverse ($\sigma = t$) electromagnetic plasma waves have the dispersion relation $\omega^t(\mathbf{k}) = [\omega_p^2 + c^2(\mathbf{k}^t)^2]^{1/2} = 2\pi f$, where c is the speed of light, f is the wave frequency, and $\omega_p = 2\pi f_p$ is the angular plasma frequency. These waves will be referred to below as photons. By analogy the longitudinal ($\sigma = L$) electrostatic oscillations, i.e., Langmuir waves of frequency $\omega^L(\mathbf{k}) = [\omega_p^2 + v_{\text{th}}^2(\mathbf{k}^L)^2]^{1/2}$, where $v_{\text{th}} = (3\kappa T_{\text{th}}/m_e)^{1/2}$ is the thermal speed of electrons of mass m_e and temperature T_{th}, are sometimes called plasmons.

Introducing the group velocity $v_g = \partial\omega(\mathbf{k})/\partial k = cN$, in terms of the local refractive index of the medium $N = kc/\omega$, the energy density of the photons (including both polarization states) may be written in the form $W = 2\kappa \int T(1/v_g)(Nf/c)^2\, df\, d\Omega$, where the integrals are over frequency f and propagation solid angle Ω (superscript σ is omitted for $\sigma = t$). For comparison with observational data, it is convenient to write the energy density of the photons in terms of the specific intensity of the source $I(f)$, or the energy flux per unit frequency and solid angle: $W = \int I(f)\,(1/v_g)\, df\, d\Omega$. The brightness (color) temperature $T(f)$ of the radiation at the frequency f is then

$$2\kappa T(f) = I(f)/(Nf/c)^2 \tag{1}$$

where $I(f) = F(f)/\Delta\Omega_s$. Now $F(f)$ is the spectral flux density, i.e., the energy flux per unit frequency, and $\Delta\Omega_s$ is the angular extent of the observed source. The brightness temperature $T(f)$ defined in equation (1) is useful because it does not vary along the ray path from the source to the observer due to refractive effects (unlike $W(\mathbf{k})$ and $I(f)$) in the absence of further emission or absorption outside the source [e.g., *Melrose*, 1980*b*]. Therefore it is possible to infer characteristics of an unknown source even if the instrument, which might detect photons escaping from this source region, is located far from the source. Furthermore, thermal emissions have $T(f)$ equal to the electron temperature T_{th} [*Melrose*, 1970].

The measured flux $F \approx (1\text{–}3) \times 10^{-17}$ W m^{-2} Hz^{-1} [*Kurth et al.*, 1984, 1987] may be used to constrain the brightness temperature of the radiation. It is shown that the local plasma frequency at the Voyager spacecraft was significantly less than the low-frequency cutoff (~2 kHz) of the radiation [*Kurth*, 1990*b*]. This implies that $N^2 \sim 1$. This value minimizes the brightness temperature: $T \approx (0.4\text{–}2) \times 10^{16}$ K/$\Delta\Omega_s$ (sr) for the 2- to 3-kHz emission in the outer heliosphere. Because obviously $\Delta\Omega_s \leq 4\pi$ sr, the value of F in equation (1) implies $T \gtrsim (\frac{1}{3}\text{–}2) \times 10^{15}$ K ($\gg m_e c^2/\kappa$) [see *Macek et al.*, 1991]. Smaller source sizes may imply substantially higher brightness temperature. In comparison, the brightness temperatures of type II and III solar radio bursts lie in the ranges 10^7–10^{13} K and 10^7–10^{16} K, respectively [*McLean and Labrum*, 1985]. Type III bursts in the solar wind have brightness temperatures in the range 10^{12}–10^{15} K. The radiation generated at the Earth's bow shock at f_p and $2f_p$ [*Cairns*, 1986; *Burgess et al.*, 1987; *Lacombe et al.*, 1988] has brightness temperatures in the ranges 10^{12}–10^{15} K and 10^9–10^{13} K, respectively. Accordingly, the minimum inferred brightness temperature of the outer heliospheric emissions lies within the ranges of the values for other known solar system sources of radiation at multiples of f_p.

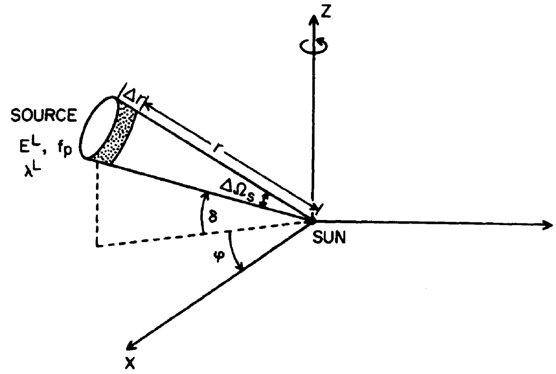

Fig. 1. Adopted geometry of the source of the radiation in the outer heliosphere.

Figure 1 shows the assumed geometry for the radiation. The power per unit solid angle, radiated in a volume $\Delta V = r^2 \Delta r\, \Delta\Omega_s$ of the source in frequency interval Δf, is denoted by ΔP. Since the intrinsic directivity of the source is unknown, we assume that the photons are emitted isotropically. Then, using flux conservation, one should have $\Delta P = r^2 F(f)\, \Delta f$. The volume emissivity is $J = \Delta P/\Delta V = I\,(\Delta f/\Delta r)$. For a given solid angle $\Delta\Omega_s$ subtended by a source, one finds again $I(f) = F(f)/\Delta\Omega_s$, where F is the flux measured near the Sun. Our interest here is with the emissions at $f \sim 2$ and 3 kHz as observed by the Voyager 1 and 2 spacecraft [*Kurth et al.*, 1984, 1987]. Taking the measured values of $F \approx 10^{-17}$ W m^{-2} Hz^{-1} and a representative frequency bandwidth of $\Delta f \sim 1$ kHz, one obtains a volume emissivity $J \sim (\frac{2}{3}) \times 10^{-25}$ W m^{-3} sr^{-1}/[Δr(AU) $\Delta\Omega_s$(sr)]. In comparison, type III bursts generated in the interplanetary medium at $r \sim 1$ AU have volume emissivity in the range 10^{-26}–10^{-19} W m^{-3} sr^{-1} [*Gurnett et al.*, 1980], and the estimated value for the Earth's $2f_p$ radiation is in the range $(\frac{1}{2}\text{–}20) \times 10^{-22}$ W m^{-3} sr^{-1} [*Lacombe et al.*, 1988]. Given the uncertainties in estimating the actual values of Δr and $\Delta\Omega_s$, it is difficult to put the limits on volume emissivity for the outer heliosphere emissions. However, for plausible source sizes ($\Delta r \sim 1$ AU and $\Delta\Omega_s \sim 0.1\pi$ sr [see *Macek et al.*, 1991]), the value of the volume emissivity $J \sim 2 \times 10^{-25}$ W m^{-3} sr^{-1} falls into the range spanned by the other sources of radiation in the solar system.

THEORETICAL CONSTRAINTS

The simplest mechanisms proposed for conversion of Langmuir waves into radiation at multiples of f_p involve

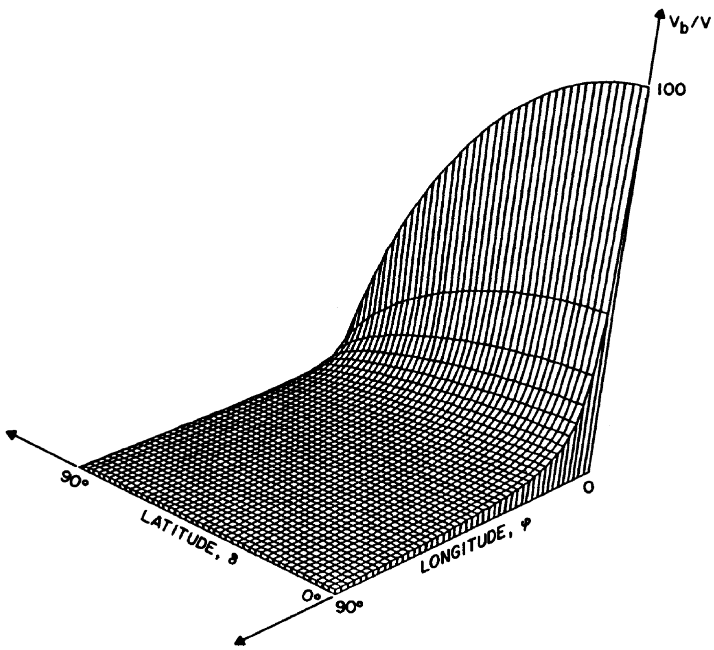

Fig. 2. Predicted average speed v_b of electrons streaming along the magnetic field in units of solar wind velocity v as a function of the heliospheric latitude δ and longitude φ (for a "nose" of the heliospheric shock located at $r = D = 100$ AU; this figure is taken from *Macek et al.* [1991]; here $\eta = v_b/c$; see text).

scattering of Langmuir waves by thermal ions [*Ginzburg and Zheleznyakov*, 1958]. In particular, in the case of $2f_p$ emission involving Langmuir waves generated by isotropic gap distributions of electrons, the temperature T^L of Langmuir waves is limited by $T^L \leq T_o \sim \frac{1}{2} m_e c^2/\kappa \sim 3 \times 10^9$ K [*Cairns and Melrose*, 1985; cf. *Fung et al.*, 1982]. Hence the measured flux F (and T) rules out this mechanism in our case.

Therefore we now consider radiation generated near multiples of f_p by nonlinear processes involving Langmuir waves. We assume that in the source, photons of energy density W are produced by a conversion process ($L \Rightarrow t$) from Langmuir waves of the energy density $W^L = \varepsilon_0 (E^L)^2$, where E^L is the average electric field strength of the Langmuir waves (ε_0 is the permittivity of free space). The energy density of Langmuir waves W^L is related to the wave temperature T^L by $W^L \sim \kappa T^L \Delta\Omega^L \psi/(\lambda^L)^3$, where $\psi = |\Delta k^L/k^L| = |\Delta\lambda^L/\lambda^L|$ is a relative bandwidth (usually not very large) of Langmuir waves with the central wavelengths $\lambda^L = 2\pi/k^L$ and $\Delta\Omega^L$ is the range of propagation solid angles. Estimates of the Langmuir wave electric field in the source may be calculated directly from this relation. Alternatively, one can manipulate the relation $F = (W/W^L)(\Delta\Omega_s/\Delta\Omega)(cN/\Delta f)W^L$, where N is the refractive index, by expanding the ratio W/W^L in terms of the ratio of the corresponding average spectral densities T and T^L. Finally, one finds the observed flux:

$$F = 2(T/T^L)\zeta(Nf/c)^2 W^L(\lambda^L)^3 \tag{2}$$

Here the relative source size parameter is defined as $\zeta = (\Delta\Omega_s/\Delta\Omega^L)/\psi$.

The nonlinear processes responsible for generating the radio emission involve an interaction of Langmuir waves with low-frequency waves such as ion acoustic waves ($\sigma = S$). These interactions are of the form $L \pm S \Leftrightarrow t(f_p)$, $L \pm S \Leftrightarrow L'$, and $L + L' \Leftrightarrow t(2f_p)$ [e.g., *Cairns and Melrose*, 1985; *Cairns*, 1988]. These nonlinear processes have constraints on the maximum brightness temperature T of the emitted radiation. For instance, the fundamental emission process $L \Leftrightarrow t(f_p) \pm S$ and the second harmonic process $L \Leftrightarrow L' \pm S$ coupled with $L + L' \Leftrightarrow t(2f_p)$ both restrict T to be less than T^L, the effective temperature of Langmuir waves. The observational data in the preceding section then require $T^L \gtrsim 3 \times 10^{14}$ K. This constraint can be used to estimate the minimum Langmuir wave electric field E^L in the source using the definition $W^L = \int \kappa T^L(\mathbf{k})\, d^3\mathbf{k}^L/(2\pi)^3 = \varepsilon_0(E^L)^2$. These Langmuir waves are usually driven by a beam of electrons streaming along the magnetic field. For example, in Figure 2 the average beam speed v_b (in units of solar wind velocity v) for a heliospheric shock (with a "nose" located at the heliospheric distance $r = D = 100$ AU) is shown as a function of the heliospheric latitude δ and longitude φ as discussed by *Macek et al.* [1991, equation (1)]. Here the beam velocity (in units of the velocity of light) is also denoted by $\eta = v_b/c$. The wavelengths of these Langmuir waves are concentrated near $\lambda^L = \eta c/f_p$ [*Cairns and Melrose*, 1985].

Consider first, for example, the coalescence of Langmuir waves with low-frequency waves ($L \pm S \Leftrightarrow t$), which have the same wavelengths as the Langmuir waves and overlap them in certain angles of propagation ($\psi^S \sim \psi^L$, $\Delta\Omega^S \sim \Delta\Omega^L$), produce photons at $f \sim f_p$. For weakly damped Langmuir waves the wavelengths λ^L are much larger than the local Debye length $\lambda_D = (v_{th}/f_p)/(2\pi 3^{1/2})$. For a process of coalescence of such a beam-driven Langmuir wave with a wave of a frequency $f^S = \omega^S/2\pi \ll f_p$, due to kinematic considerations, one has $kc \approx k^L v_{th}$. This implies that $N \approx v_{th}/(f_p \lambda^L)$ should be small in the source region. Using equation (2), one finds

$$F \sim 2(T/T^L)\zeta(c/f_p)(v_{th}/c)^2 \eta W^L \quad (3)$$

Now, for a saturation of the nonlinear process one would have $T \sim T^L$ [*Melrose*, 1980*a*, *b*]. Hence assuming that the observed radiation at 3 kHz lies just above f_p, with the refractive index corresponding approximately to the distant source region ($N \sim 0.05$), and taking the observed value of F at $f_p \sim 3$ kHz, equation (3) implies a minimum wave electric field $E^L \sim 1$ mV/m/$[\zeta T_{th}(\text{eV})\eta]^{1/2}$ in the source.

As a numerical example, we take $\eta \sim 0.15$, which is the maximum value at the heliospheric shock at the nose located near the direction of the apex at distance $D = 100$ AU (see Figure 2, the solar wind velocity $v = 450$ km s^{-1} $= 0.0015c$) as obtained by *Macek et al.* [1991] using their source model. Taking a source size of $\Delta\Omega_s \sim 0.1\pi$ sr resulting from Figure 2 and the electron temperature $T_{th} \sim 10$ eV [cf. *Burlaga et al.*, 1990] and other nominal source parameters ($\psi \sim 0.1$–1.0, $\Delta\Omega^L \sim 0.1$–1.0 sr), one finds a minimum field $E^L = 0.15$–1.5 mV/m in the source region. Assuming, for example, that $f_p \ll 3$ kHz and $N^2 \sim 1$ instead, one finds directly from equation (2) $E^L \sim 7$–70 μV/m.

Second, the process of coalescence of two Langmuir waves with the same wavelengths and oppositely directed wave vectors $L + L' \Leftrightarrow t$ could produce the photon with frequency $f \sim 2f_p$. Now one obtains $(kc)^2 \sim 3\omega_p^2$ and large $N^2 \sim 3/4$. This means that refractive effects are significant for the fundamental emission but they are not for the second-harmonic emission. Using equation (2), one finds for the $2f_p$ emission

$$F \sim (T/T^L)(6c/f_p)\zeta\eta^3 W^L \quad (4)$$

In the steady state the observed flux F at $2f_p \sim 3$ kHz in equation (4) would imply $E^L \sim 1$ μV/m/$(\zeta\eta^3)^{1/2}$. Taking the same values ($\eta \sim 0.15$, $\Delta\Omega_s \sim 0.1\pi$ sr, $\psi \sim 0.1$–1.0, $\Delta\Omega^L \sim 0.1$–1.0 sr), now one finds the lower value of the average field $E^L = 3$–30 μV/m required in the source region. In Figure 3 the electric field of electron plasma oscillations measured near planetary bow shocks at Earth, Jupiter, Saturn, Uranus, and Neptune [*Gurnett et al.*, 1989, and references therein] are shown by solid bars. The minimum field strength of the Langmuir waves in the outer heliosphere is presented by a dotted bar. Hence this value is quite plausible.

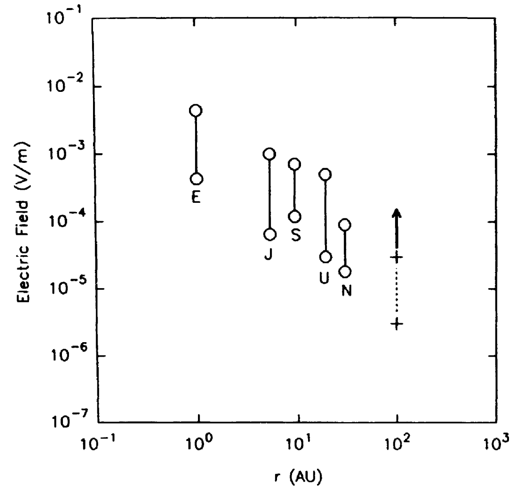

Fig. 3. Comparison of the electric field of electron plasma oscillations measured near planetary bow shocks at Earth, Jupiter, Saturn, Uranus, and Neptune (solid bars) [*Gurnett et al.*, 1989]. The minimum average field strength of the Langmuir waves in the outer heliosphere, as calculated here (for $f \sim 2f_p$), is shown by a dotted bar.

SATURATION LENGTH

The required conversion rate in terms of the emissivity (on the average) is $\nu = J\,\Delta\Omega/W^L$. One obtains $\nu = (F/W^L)(\Delta f/\Delta r)(\Delta\Omega/\Delta\Omega_s)$ (if the photons are emitted isotropically, $\Delta\Omega = 4\pi$). On the other hand, the theoretical conversion rate ν' is defined by $v_g\,(dW/dr) = \nu' W^L$, where r denotes distance along the ray path in the source. Assuming that the energy density W^L is constant in the source, one has $\nu' \sim (cN/\Delta r)(W/W^L)$. Assuming the theoretical conversion rate is equal to the conversion rate computed from the volume emissivity ($\nu' = \nu$) and using equation (2), one obtains

$$\nu' \sim 2(T/T^L)\,(\Delta\Omega/\Delta\Omega^L/\psi)\,(Nf/c)^2\,(\Delta f/\Delta r)\,(\lambda^L)^3 \quad (5)$$

For scattering of Langmuir waves by thermal ions the rate of conversion in terms of the Thompson cross-section $\sigma_T = (8\pi/3)r_e^2$, where $r_e = e^2/(4\pi\varepsilon_0 m_e c^2)$ is the classical electron radius, is approximately given by the well-known classical rate $\nu_T = \sigma_T n_e c N$. If the effective temperature T^S of S waves is sufficiently large, the nonlinear process $L \pm S \Leftrightarrow t$ generates the radiation at a rate $\nu = \nu_T T^S/T_{th}$, which is considerably higher than the standard mechanism by scattering of thermal ions [*Melrose*, 1980*b*]. Transverse waves in a range Δf can be generated over a range of distances $\Delta r = 2L_n\Delta f/f$, where $L_n = n_e/|dn_e/dr|$ is the characteristic distance over which the plasma density n_e varies. It follows from equation (5) that the required energy density in the S waves [cf. *Melrose*, 1980*b*] is

$$W^S \sim 6\varepsilon_0(T/T^L)\kappa T_{th} N f_p/(cr_e L_n) \quad (6)$$

According to equation (6) one sees that the fundamental emission process saturates provided that the ratio of the electric field of S waves to the electric field of Langmuir waves exceeds a small value of $\sim 4 \times 10^{-4}$ $T_{th}^{5/4}$ (eV) $[\zeta/L_n(\text{AU})]^{1/2}$.

For the process $L + L' \Leftrightarrow t$, assuming that Langmuir waves are isotropic and that the so-called "head-on" approximation is valid [*Melrose*, 1980*b*], the theoretical estimate for the rate is $\nu' \approx 1.2\nu_T\kappa T^L/(m_e c^2)$. In a similar way, one finds

$$W^L \sim \varepsilon_0(T/T^L)20mcNf/(r_e L_n) \quad (7)$$

However, equation (7) and saturation would imply that the scale length $L_n \sim 1$ AU $\zeta\, d^3 T_{th}^{3/2}$ (eV), where the parameter $d = \lambda^L/10\lambda_D \gtrsim 1$. For beam-driven Langmuir waves one obtains $d^3 T_{th}^{3/2}$ (eV) $\sim 9 \times 10^7$ η^3. The resulting scale length is then $L_n \sim 9 \times 10^7$ AU $\zeta\eta^3$. For example, with $\eta \sim 0.1$, $\zeta \sim 0.1\pi$, one has $L_n \sim 10^4$ AU. This number is too large.

These foregoing estimates assume saturation at $T \sim T^L$. However, the radiation processes need not saturate, thereby permitting $T^L \gg T$ and accordingly much smaller source dimensions. For example, increasing T^L by a factor of $\sim 10^2$ relative to T reduces the required length by a factor of 10^4, thereby permitting a source size of the order of 1 AU. Alternatively, the beam speed $\eta = v_b/c$ could be smaller, also reducing the required size of the source. Finally, strong turbulence may be more efficient at producing f_p and $2f_p$ radiation than the weak turbulence discussed here. A detailed discussion of path lengths for the radiation and the source dimensions will be given elsewhere.

POSSIBLE SOURCE MODEL

The solar wind (sunward) side of the inner heliospheric shock is expected to be the side of the shock with low number density and low magnetic field [*Fahr et al.*, 1986]. Accordingly, by analogy with planetary bow shocks, drift acceleration and mirror reflection of solar wind electrons (and leakage of downstream electrons) may be expected to produce energized electrons streaming sunward from regions of the heliospheric shock where the beam velocity v_b is large.

As it is well known from quasi-perpendicular planetary bow shocks [*Gurnett*, 1975; *Filbert and Kellogg*, 1979; *Melrose*, 1980*a*; *Cairns*, 1986, 1987, 1988], electrons energized at regions of the shock where v_b is large generate high levels of electrostatic Langmuir plasma waves. Also at the heliospheric shock the beam electrons should produce Langmuir waves as argued by *Macek et al.* [1991]. The almost tangential magnetic field should severely limit the radial extent of the Langmuir wave source region. Nevertheless, as it follows from our consideration of the radiation mechanism, a large source, of the order of 1 AU, is expected. Taking $v = 0.0015c$ and $D = 100$ AU (see Figure 2), one finds $v_b \sim 0.15c$ near the nose of the heliospheric shock. The resulting Langmuir wavelengths are then $\lambda^L \sim 30$ km. For $2f_p \sim 3$ kHz and T_{th} of several eV [cf. *Burlaga et al.*, 1990], one expects a Debye length $\lambda_D \sim 10^2$ m upstream of the shock and obviously $\lambda^L \gg \lambda_D$. Hence it is likely that the Langmuir waves in the source should be only weakly damped.

Voyager 1 is traveling with a velocity of 3.5 AU/yr at ~35° north of the ecliptic and is expected to be at $r \sim 50$ AU in 1992 and $r \sim 100$ AU in 2006. After Neptune, Voyager 2 is traveling ~50° south of the ecliptic (Pioneer 11 is closer to the apex). As one can see from Figure 2, it is fortunate that the beam velocity and, consequently, the measured wave amplitude and flux spectral density given by equation (4) are less sensitive to the latitudinal than to the longitudinal variations from the actual nose of the shock. Hence all these spacecraft may be approaching the regions of the heliospheric shock, where the calculated v_b is large. These spacecraft are therefore proceeding toward a likely source region for Langmuir waves. However, the Voyager 1 and Voyager 2 spacecraft will not have enough power to operate beyond the year 2017, when they will be at $r \sim 138$ AU and $r \lesssim 113$ AU, respectively. If the termination shock is located at $r \lesssim 100$ AU or so, these Langmuir waves may, in principle, be observed in situ in the foreseeable future.

CONCLUSION

In conclusion, we have estimated that the minimum field strength of Langmuir waves required to generate the 3-kHz radio emission in the outer heliosphere is approximately 3–30 μV/m. These field strengths have been shown to be plausible on the basis of the electric fields of Langmuir waves observed upstream from planetary foreshocks.

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