

Fig. 1. Schematic illustration of the expected shock system formed by the interaction of the solar wind and the plasma component of the interstellar medium. The heliopause separates the flows of the shocked solar wind and interstellar plasmas.

and Zheleznyakov, 1959; Melrose, 1980a,b, 1986; McLean and Labrum, 1985; Cairns, 1988a,b]. Our objective in this paper is to place constraints on the characteristics of the emission processes and source regions capable of generating radiation at multiples of f_p with the intensity of the observed 2- to 3-kHz radio emissions. Only weak turbulence processes are considered. A new source model for the radiation, a foreshock region sunward of the inner heliospheric shock [Macek et al., 1991a], is presented and discussed in a companion paper [Cairns et al., this issue]. The calculations presented here indicate that the levels of Langmuir waves expected in this foreshock are sufficient to generate the observed radio emissions in a distance small compared with 1 AU and the expected dimensions of the foreshock. Alternative interpretations for the observed signals, such as continuum radiation from Jupiter or Saturn and quasi-thermal plasma noise, are discussed elsewhere [Kurth et al., 1984, 1986, 1987; Meyer-Vernet, 1989; Kurth, 1990].

Section 2 introduces the theoretical formalism used to treat the wave-wave processes generating the radiation, motivates the use of the brightness temperature of the radiation and wave temperatures for the Langmuir waves, and summarizes calculations [Macek et al., 1991a,b] of the minimum brightness temperature for the radio emissions. The observed brightness temperatures are then used to constrain the source of the Langmuir waves and to rule out certain emission mechanisms for the radiation (section 3). Minimum values for the Langmuir wave field strengths are derived and compared with observed values at planetary bow shocks. Path lengths required for the radiation to reach the observed levels using emission mechanisms involving ion acoustic waves [e.g., Melrose, 1980a,b, 1986; Cairns, 1988a,b] are then derived and discussed (section 4). The Langmuir wave effective temperatures, electric field intensities, and the ratio of wave to thermal plasma energy required for the

radiation source to be less than 1 AU in thickness are discussed in section 5. These results are used to constrain the location of the radiation source in the outer heliosphere (section 6). Brief mention is made in section 6 of the new source location for the radiation discussed in detail by Cairns et al. [this issue]: a foreshock region filled with energetic electrons and Langmuir waves sunward of the inner heliospheric shock. Concluding remarks and a summary of the paper are given in section 7.

2. FORMALISM AND OBSERVED BRIGHTNESS TEMPERATURES

Most treatments of radiation at multiples of f_p use a semiclassical, weak turbulence formalism in which waves are regarded as a collection of wave quanta. Detailed descriptions of this formalism are given in the works of Tsytoich [1966], Melrose [1980a,b, 1986], and Cairns [1987a, 1988a,b] among others. Here we only introduce the important physical quantities necessary for this paper and refer more detailed questions to the above mentioned works. The total energy density W_σ of waves in the mode σ is related to the effective wave temperature $T_\sigma(k)$ of waves with wave vector k by

$$W_\sigma = \int k_B T_\sigma(k) d^3k / (2\pi)^3 \quad (1)$$

where k_B is Boltzmann's constant. The wave temperature T_σ then equals the spectral energy density divided by k_B ; i.e., T_σ is proportional to the energy density per elemental range $d^3k / (2\pi)^3$ in wave vector space. Wave temperatures play a fundamental role in the work described here. Radio waves are transverse electromagnetic plasma waves with dispersion relation $\omega(k) = (\omega_p^2 + c^2 k^2)^{1/2} = 2\pi f$, where c is the speed of light, f is the wave frequency, and $\omega_p = 2\pi f_p$ is the angular plasma frequency. Langmuir waves ($\sigma = L$) are electrostatic with (formal) dispersion relation $\omega_L(k) = (\omega_p^2 + 3k_L^2 V_e^2)^{1/2}$, where $V_e = (k_B T_e / m_e)^{1/2}$ is the thermal speed of electrons with temperature T_e . Introducing the group velocity $v_g = \partial\omega(k) / \partial k = cN k/k$ and the refractive index of the medium, $N = kc/\omega$, the energy density of the electromagnetic waves (including both polarization states) may be written in the form $W = 2k_B \int T(1/v_g)(Nf/c)^2 df d\Omega$, where the integrals are over frequency and solid angle. For comparison with observational data it is convenient to write the energy density of the photons in terms of the specific intensity $I(f)$, otherwise known as the energy density flux per unit frequency and unit solid angle: $W = \int I(f)(1/v_g) df d\Omega$. Here, and below, observational quantities are assumed to be averages over the source region. The brightness temperature $T(f)$ of the radiation at the frequency f is then

$$T(f) = \frac{I(f)}{2k_B(Nf/c)^2} \quad (2)$$

In this equation, $I(f) = F(f)/\Delta\Omega_s$, where $F(f)$ is the flux density per unit frequency and $\Delta\Omega_s$ is the angular extent of the observed source. We emphasize that N is the refractive index of waves at frequency f and flux density $F(f)$ at the observation point (and not in the source region). From an observational point of view, the great utility of the brightness temperature $T(f)$ is that it is ideally constant (unlike $W(k)$, $I(f)$, and $F(f)$) along the ray path from the source to the observer, even in a medium with spatially varying

refractive index, provided only that no further emission or absorption occurs outside the source [e.g., *Melrose*, 1980b]. Reliable estimates of the characteristics of the radiation leaving the source region can therefore be made far from the source. There are two effects that can complicate this simple picture: scattering and trapping. Scattering of the radiation by density inhomogeneities may increase the apparent size and so decrease the apparent brightness temperature from its true value just outside the source [e.g., *Steinberg et al.*, 1985; *Lacombe et al.*, 1988]. The measured brightness temperature is then a lower limit to the brightness temperature. If the true and scattered source sizes $\Delta\Omega_t$ and $\Delta\Omega_s$ are known, then multiplying the measured brightness temperature by the ratio $\Delta\Omega_s/\Delta\Omega_t$ gives an estimate of the radiation's brightness temperature just outside the source. Trapping of radiation in a density cavity, such as continuum radiation in planetary magnetospheres [*Gurnett*, 1975], leads to the observed brightness temperature being larger than the brightness temperature of radiation leaving the source region. The relative importance of scattering and trapping effects in the outer heliosphere is currently unknown (see, however, *Cairns et al.*, [this issue]). It is most probable, however, that scattering will dominate trapping (at least for the brighter 3-kHz emissions) so that the observed brightness temperature is smaller than the brightness temperature of the radiation leaving the source region. Lastly, a final advantage of using brightness temperatures is that thermal emissions have $T(f)$ equal to the electron temperature T_e [*Melrose*, 1970].

The flux density of the observed outer heliospheric radio emissions is estimated to be approximately $F \sim (1-3) \times 10^{-17}$ W m⁻² Hz⁻¹ [*Kurth et al.*, 1984, 1987]. These flux densities may be used to constrain the brightness temperature of the radiation. Although evidence exists that the local plasma frequency sometimes approaches the upper frequency (~ 3 kHz) of the radio emissions, the local plasma frequency is typically well below 2 kHz when the radio emissions are observed [*Kurth et al.*, 1987; *Kurth*, 1990]. This implies that $N^2 \sim 1$ in equation (1). Noting that this value of N^2 minimizes the brightness temperature and that $\Delta\Omega_s \leq 4\pi$ sr, equation (1) implies a minimum brightness temperature $T = (3-20) \times 10^{14}$ K [*Macek et al.*, 1991a,b]. Smaller source sizes may imply substantially higher brightness temperatures. For instance, when $\Delta\Omega_s = 1$ sr the corresponding brightness temperatures are $(4-20) \times 10^{15}$ K. Note that these source sizes include the effects of any scattering or trapping of the radiation, thereby probably underestimating the true brightness temperature of the radiation leaving the source. Both f_p and $2f_p$ radiation from type III bursts in the solar wind, and $2f_p$ radiation from Earth's foreshock, are strongly scattered in the solar wind [*Steinberg et al.*, 1985; *Lacombe et al.*, 1988]. This is also likely to be the case for the outer heliospheric radio emissions.

Concern might be expressed over the high minimum brightness temperature of the outer heliospheric radio emissions. However, these calculated brightness temperatures lie within the ranges of brightness temperatures for known sources of radiation at multiples of f_p in our solar system, such as type II and III solar radio bursts and the Earth's f_p and $2f_p$ radiation [*Macek et al.*, 1991b]. A similar result follows for the volume emissivity of the observed radio emissions for plausible source dimensions in the outer heliosphere [*Macek et al.*, 1991b].

3. THEORETICAL CONSTRAINTS RESULTING FROM THE BRIGHTNESS TEMPERATURE

The simplest mechanisms proposed for converting Langmuir waves into radiation at multiples of f_p involve scattering by thermal ions [*Ginzburg and Zheleznyakov*, 1959]. However, *Melrose* [1980a,b] showed that scattering processes involving low-frequency waves, such as ion acoustic waves ($\sigma = S$), naturally have greater conversion rates by a factor of order T_S/T_e (where T_S is the effective temperature of the ion acoustic waves and $T_S \geq T_e$). Therefore in this paper we only consider radiation generated near multiples of f_p by nonlinear processes involving Langmuir and ion acoustic waves. Examples of these nonlinear processes include the fundamental emission processes $L \pm S \rightarrow \iota(f_p)$, the coupled second harmonic emission processes $L \pm S \rightarrow L'$ and $L + L' \rightarrow \iota(2f_p)$, and the third harmonic emission process $L + \iota(2f_p) \rightarrow \iota(3f_p)$ [e.g., *Melrose*, 1980a,b; *Cairns and Melrose*, 1985; *Cairns*, 1987a, 1988a,b]. These nonlinear processes have constraints on the maximum brightness temperature T for the radiation in terms of the levels of participating Langmuir waves [e.g., *Melrose*, 1970, 1980a,b; *Cairns*, 1987a, 1988a,b]. The emission processes specified above, and both their analogues with other low-frequency waves and higher-order processes (i.e., four-wave processes), all require T and the effective temperature T_L of the Langmuir waves to obey

$$T \leq T_L, \quad (3)$$

even if $T_S > T_L$ [*Melrose*, 1980a,b, 1986; *Cairns*, 1988a,b]. The observational data in the previous section then require $T_L \geq 3 \times 10^{14}$ K. This constraint may be used to place requirements on the source of the participating Langmuir waves, to rule out an emission mechanism, and to estimate the minimum rms field strengths E_L of Langmuir waves in the source.

Thermal mechanisms for producing the Langmuir waves are ruled out since $T_e \ll 3 \times 10^{14}$ K. The only other stable source for Langmuir waves previously suggested in connection with radiation at multiples of f_p involves isotropic gap distributions of electrons [e.g., *Fung et al.*, 1982]. However, balancing absorption and spontaneous emission, the maximum effective temperature of these Langmuir waves is $T_L \sim 0.5 m_e c^2/k_B \sim 3 \times 10^9$ K [*Cairns and Melrose*, 1985]. Hence the observed outer heliospheric radio emissions cannot be radiation at multiples of f_p resulting from this source of Langmuir waves. With thermal and known stable mechanisms for producing the required Langmuir waves ruled out, a plasma instability is the only remaining source for the high levels of Langmuir waves required to produce the observed radiation. An electron beam instability is the most plausible source for the Langmuir waves. Beam-driven Langmuir waves are concentrated near a wavenumber $k_L = 2\pi f_p/v_b$ and wavelength $\lambda_L = v_b/f_p$, where v_b is the beam speed. Further restrictions on the wave vectors of Langmuir waves able to participate in the wave-wave processes are given by kinematic constraints [e.g., *Cairns*, 1987a, 1988a,b].

Estimates of the minimum electric rms field strengths of Langmuir waves in the source may be calculated directly from the definition $W_L = \int k_B T_L(k) d^3 k / (2\pi)^3 = \epsilon_0 (E_L)^2$, the constraint $T_L \geq T$, and an estimate of the volume in wave vector space occupied by the participating Langmuir waves. Assuming

that the wave temperature T_L is constant over the domain of interest, one has

$$W_L \sim k_B T_L \Delta\Omega_L (k_L/2\pi)^3 \Delta k_L/k_L. \quad (4)$$

Here $\Delta k_L/k_L$ is the relative bandwidth of Langmuir waves with central wavenumber k_L , and $\Delta\Omega_L$ is the range of solid angles filled by the waves. Similar calculations have been performed by Cairns and Melrose [1985], Cairns [1988a], and Macek *et al.* [1991b]. Note that the minimum Langmuir wave electric field in the plasma is independent of whether the radiation is f_p , $2f_p$, or $3f_p$ radiation for the same Langmuir phase space volume and brightness temperature.

Kinematic constraints (energy and momentum conservation) on waves participating in the fundamental emission processes $L \pm S \rightarrow t$ are described by Cairns [1987a]. Restrictions on k_L for the coalescence process are not severe; for the decay process one requires $k_L > k_0 = 2\omega_p V_S / 3V_e^2$ with $k_L = \omega_p/v_b$, where $V_S = (k_B T_e (1 + 3T_i/T_e)/m_i)^{1/2}$ is the ion acoustic speed and v_b is the beam speed. For the parameters expected in the outer heliosphere ($T_e = 10^4$ K and $T_i/T_e \sim 3$), this constraint requires $v_b < 2 \times 10^7$ m s⁻¹. A similar constraint ($k_L > 3k_0/2$) exists for the decay $L \rightarrow L' + S$ involved in the $2f_p$ emission process [Cairns, 1988a]: $v_b < 3 \times 10^7$ m s⁻¹. Requiring T_L to equal the brightness temperature of the radiation and rearranging equations (2) and (4), the minimum field strength of Langmuir waves in the source is

$$E_L \sim 10^{-6} \left(\frac{\Delta\Omega_L}{\Delta\Omega_s} \frac{\Delta k_L}{k_L} \frac{c^3}{v_b^3} \right)^{1/2} \text{ V m}^{-1}. \quad (5)$$

The constant of proportionality in this equation, 10^{-6} , is determined by physical constants, an assumed plasma frequency of 1.5 kHz, and the frequencies and flux densities of the observed radiation.

Taking $v_b \sim 0.1c$, consistent with the kinematic constraints above, nominal parameters $\Delta\Omega_L \sim 0.1-1$ sr and $\Delta k_L/k_L = 0.1-1$ for the Langmuir wave spectrum, and a source size for the radiation $\Delta\Omega_s \sim 0.4-4\pi$ sr, one finds minimum electric fields in the range 1–100 $\mu\text{V m}^{-1}$ in the source region. Smaller beam speeds will increase these electric fields. (The electric field of order 1 mV m⁻¹ quoted by Macek *et al.* [1991b] for f_p radiation is in error. This error, retained personally by Macek, results from incorrectly combining a low refractive index $n = 0.05$ in the source region with the flux density measured by Voyager where $n \sim 1$.) We emphasize that these are the minimum electric fields imposed by the requirement that $T_L \geq T$ and the above kinematic constraints on v_b . As shown in the next section, larger Langmuir wave temperatures T_L and electric fields may be required for production of the observed radiation in a reasonable source volume.

The solid bars in Figure 2 show the rms field strengths of Langmuir waves observed by the Voyager spacecraft in the foreshocks of Earth, Jupiter, Saturn, Uranus, and Neptune [Gurnett *et al.*, 1989 and references therein] as a function of heliocentric distance. The shaded region in Figure 2 is formed by combining the minimum Langmuir wave fields determined above with a range of likely heliocentric positions for the source region. Clearly the minimum Langmuir electric fields fall naturally into the range obtained by extrapolating the upper and lower envelopes of planetary foreshock fields to larger heliocentric distances.

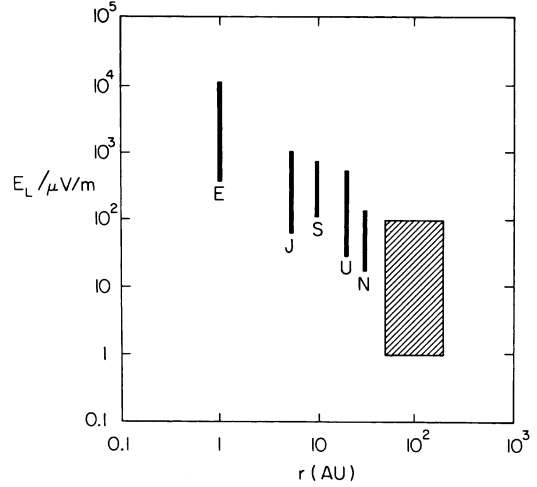


Fig. 2. The electric fields of Langmuir waves observed in the planetary foreshocks of Earth, Jupiter, Saturn, Uranus, and Neptune are shown as a function of heliocentric distance using solid bars. The shaded box shows the minimum average field strength of the Langmuir waves in an outer heliospheric source given by kinematic arguments involving the observed brightness temperatures of the radiation. Calculations in sections 4 and 5 show that average Langmuir wave fields in the shaded box are sufficient to generate the observed levels of radiation in path lengths smaller than 1 AU under various conditions.

These minimum required fields are therefore very plausible based on observational data in planetary foreshocks. Interpreting the radio emissions as f_p and $2f_p$ radiation generated by Langmuir waves therefore remains possible.

4. PATH LENGTHS FOR GENERATING RADIATION

The path lengths required for the radiation to reach the observed levels may be estimated using specific models for the radiation processes and estimates of the effective temperatures T_L and phase space volume of the participating Langmuir waves. Consider first fundamental radiation produced near f_p by the decay process $L \rightarrow t(f_p) + S$. Factors strongly favoring the decay process over the corresponding coalescence process $L + S \rightarrow t(f_p)$ include [Cairns, 1987a] the following: (1) nonthermal levels of both L and S waves are required before the coalescence process can proceed, while only nonthermal L waves are required for the decay to proceed; (2) the decay process is an amplifying process, while the coalescence process is not. The temperature $T(s)$ of radiation produced by the (amplifying) decay process after a path length s is given by [Cairns, 1987a]

$$T(s) = \frac{1}{2} (T(0) + T_S(0)v_b/V_S) \exp(2AT_L s) - \frac{1}{2} (T_S(0)v_b/V_S - T(0)) \quad (6)$$

where

$$A = \frac{k_B e^2 f_p^2 (1 + 3T_i/T_e)^2}{24\sqrt{3} \epsilon_0 m_e m_i c V_S v_b^3} \Delta\Omega_L \sin^2 \theta_{TL}. \quad (7)$$

Here $T(0)$ and $T_S(0)$ are the initial effective temperatures ($\sim T_p$) of the radiation and ion sound waves, respectively, $\Delta\Omega_L$ is the solid angle of wave vector space filled by the Langmuir waves, θ_{TL} is the spectrum-averaged angle between the wave vector of an observed radio photon and the Langmuir waves, and the central (or primary) Langmuir wave vector is $k_L = \omega_p v_b / v_b^2$. The requirement for producing very large levels of radiation, even levels close to the saturation level $T(s) = T_L$ (where equation (6) no longer applies due to neglect of the back-reaction term), is specified by the exponential term in equation (6):

$$2AT_L s \sim 30. \quad (8)$$

For the radio emissions in the outer heliosphere we take $T_e = 10^4$ K, $T_e/T_i = 3$, $f_p = 1.5$ kHz, $\Delta\Omega_L = 0.1$, and $\theta_{TL} = 45^\circ$. Then this last equation may be rearranged to give the minimum path length s in astronomical units:

$$s \sim 8 \times 10^7 \frac{v_b}{T_L}. \quad (9)$$

Noting that kinematic constraints require $v_b < 1.8 \times 10^7$ m s⁻¹ and $T_L > 3 \times 10^{14}$ K, one finds that $s < 5$ AU.

Path lengths of order 5 AU are large, even on the scale of the outer heliosphere. However, path lengths significantly less than 1 AU may result from smaller beam speeds and larger Langmuir wave temperatures; for example, when $T_L = 10^{17}$ K, $s < 0.02$ AU for the above beam speed. Thus, this emission process could produce the observed levels of radiation in a source small compared with 1 AU, provided the intensities of the Langmuir waves are large enough. Below we will argue that these larger Langmuir wave temperatures are not ruled out by either the available observational data or experience at other sources of radiation at multiples of f_p .

The path length of $2f_p$ radiation generated by the coalescence $L + L' \rightarrow t(2f_p)$ may be discussed in a similar way. This emission process is not an amplifying process, and the brightness temperature of the waves grows linearly with path length s in the approximation that T_L and $T_{L'}$ are constant in the source region and $T(s) \ll T_L, T_{L'}$, [e.g., Cairns, 1988a]:

$$T(s) = BT_L T_{L'} \quad (10)$$

with

$$B = \frac{k_B e^{2f_p^2}}{4\sqrt{3} \epsilon_0 m_e^2 c^3 v_e^2 v_b} \Delta\Omega_L \sin^2 \theta \cos^2 \theta. \quad (11)$$

Here θ is the spectrum-averaged angle between the wave vector of the radiation and the Langmuir wave vectors. Taking $\theta = 45^\circ$ and the other parameters above, this equation may be rewritten to give the path length in astronomical units,

$$s = 7 \times 10^{10} \frac{v_b T(s)}{T_L T_{L'}}. \quad (12)$$

Incorporating the kinematic constraint $v_b \leq 3 \times 10^7$ m s⁻¹ and assuming saturation of the radiation processes at the minimum observed brightness temperature for the radiation ($T = T_L = T_{L'} = 3 \times 10^{14}$ K), one finds that $s \leq 7 \times 10^3$ AU, an unrealistic source dimension. Similarly, noting that $v_b > v_e$ for effective

growth of Langmuir waves, the minimum path length for the radiation process with these source parameters is 100 AU. Once again, however, variations in the beam speed v_b and Langmuir temperature T_L have strong influences on the path length required for the radiation to reach a temperature $T(s)$. For $T_L = T_{L'} = 10^{17}$ K, $T = 10^{15}$ K, and $v_b = 2.4 \times 10^7$ m s⁻¹, one finds $s = 0.2$ AU. Thus the fundamental and second harmonic emission processes discussed here can both produce the observed levels of radiation in small regions of the outer heliosphere (~ 0.1 AU) provided that the relevant Langmuir waves have $T_L \sim 10^{17}$ K.

The third harmonic emission process $L + t(2f_p) \rightarrow t(3f_p)$ requires larger path lengths than $2f_p$ emission processes since highly nonthermal levels of $2f_p$ radiation are required before production of nonthermal $3f_p$ radiation. Assuming that the brightness temperature of the $2f_p$ radiation, T_2 , and T_L are constant [Cairns, 1988b],

$$T(s) = A_2 T_L T_2 s \quad (13)$$

with $A_2 = 1.1 \times 10^{-39} f_p^2$. Taking $f_p = 1$ kHz,

$$s = 6 \times 10^{21} \frac{T(s)}{T_L T_2} \text{ AU}. \quad (14)$$

Accordingly, assuming $T(s) \sim T_2$ as required by the data, the required path lengths are of order 6×10^4 AU even with $T_L = 10^{17}$ K. Reasonable path lengths of 1 AU or less require $T_L \geq 6 \times 10^{21}$ K. Production of $3f_p$ radiation with the observed brightness temperatures therefore requires much greater Langmuir wave levels and/or source sizes than f_p or $2f_p$ radiation. While this constitutes a major potential difficulty for interpreting the 3-kHz waves as $3f_p$ radiation, similar theoretical difficulties exist for the Earth's infrequently observed $3f_p$ radiation [Cairns, 1988b].

Before discussing the plausibility of such Langmuir wave levels we consider the path length required for saturation of the decay $L \rightarrow L' + S$. Arguments [e.g., Cairns, 1988a] similar to those above for the fundamental emission process $L \rightarrow t + S$ imply that the decay process is favored, relative to the coalescence process $L + S \rightarrow L'$, to produce the backscattered L' waves participating in the coalescence process $L + L' \rightarrow t$. The backscattered Langmuir waves obey equations similar to (6)–(8). The condition for saturation of the process (at $T_L = T_{L'}$) is [e.g., Cairns, 1988a]

$$s = \frac{720 \epsilon_0 m_e^2 V_e^4 v_b^2}{k_B e^2 (1+3T_i/T_e) f_p^2 T_L \Delta\Omega_L}. \quad (15)$$

For the above source parameters, Langmuir wave solid angle $\Delta\Omega_L$, beam speeds $v_b < 2.5 \times 10^7$ m s⁻¹ as required by kinematic constraints, and $T_L > 3 \times 10^{14}$ K, one finds $s < 0.01$ AU. Similarly, when $T_L = 10^{17}$ K, $s = 3 \times 10^{-5}$ AU, compared with 0.02 AU and 0.2 AU for the fundamental and second harmonic emission processes, respectively. Thus, for the same T_L , the decay $L \rightarrow L' + S$ saturates in path lengths very small compared with those for the emission processes $L \rightarrow t + S$, $L + L' \rightarrow t$, and $L + t \rightarrow t$.

As illustrated by the foregoing calculations, the effective temperatures T_L (and $T_{L'}$) and the phase space volumes of the participating Langmuir waves are very important parameters for

determining whether these emission processes can produce the observed radiation in reasonable source volumes. There is a large degree of uncertainty in estimating T_L . However, we will now argue that T_L is likely to be considerably larger than the minimum possible value of 3×10^{14} K specified by the observed levels of radiation. First, the angular size of the radiation source cannot be specified precisely from the available data. Without this source size, only a lower limit to the brightness temperature of the radiation, and so the Langmuir wave effective temperature T_L , may be specified. Second, scattering of radiation near f_p and $2f_p$ by density irregularities may significantly increase the apparent size of the source, leading to a significant underestimate of the brightness temperature of radiation leaving the source, and so T_L . Such scattering is familiar in the case of type III solar radio bursts in the solar wind [e.g., *Steinberg et al.*, 1985]: scattering increases the source size by a factor of order 10. Assuming a similar factor here, the minimum Langmuir wave temperature T_L is increased by a factor of order 10 to 3×10^{15} K. Third, there is no guarantee that the radiation process does in fact saturate in the source region with $T = T_L$. In this case, T_L may be significantly larger than even the true brightness temperature in the source. Experience with other similar sources of radiation suggests that often the radiation processes do not saturate. For instance, theoretical calculations and observational data for the Earth's $2f_p$ radiation [*Cairns*, 1988a] are consistent with Langmuir waves with $T_L \sim 10^{15} - 10^{18}$ K producing $2f_p$ radiation with brightness temperatures of $10^{10} - 10^{13}$ K, well below the saturation temperature $T = T_L$. Similar comments apply to type III bursts in the corona [e.g., *Melrose*, 1980b], while type III bursts in the solar wind may approach saturation [*Melrose et al.*, 1986]. Lastly, and perhaps most importantly, in section 5 below we show that the ranges of Langmuir wave temperatures T_L inferred for the foreshocks of Earth and the outer planets all span the values $10^{17} - 10^{18}$ K with upper values of order 10^{20} K. We conclude, in summary, that it is not unreasonable to consider Langmuir waves with effective temperatures significantly in excess of 10^{15} K as the source of the observed radiation. This permits the source of the radiation to have dimensions significantly smaller than 1 AU.

5. ELECTRIC FIELDS IN THE SOURCE REGION

The electric field in the source region is specified by the Langmuir wave effective temperature T_L , the phase space volume occupied by the Langmuir waves, and the definition of the Langmuir wave energy density W_L :

$$E_L^2 = \Delta\Omega_L \frac{\Delta k_L}{k_L} \left(\frac{f_p}{v_b}\right)^3 \frac{k_B T_L}{\epsilon_0} . \quad (16)$$

Writing $f_p = 1.5$ kHz and $\Delta\Omega_L = \Delta k_L/k_L = 0.1$, this becomes

$$E_L^2 = 5 \times 10^{-5} \frac{T_L}{v_b^3} \text{ V}^2 \text{ m}^{-2} . \quad (17)$$

Thus, for $T_L = 10^{17}$ K, the electric field strengths E_L in the source region are of order $70 \mu\text{V m}^{-1}$ and ~ 2 mV/m for beam speeds of 10^7 m s^{-1} and 10^6 m s^{-1} , respectively. Wave field strengths of order $100 \mu\text{V m}^{-1}$ or below can therefore easily be obtained for Langmuir waves with $T_L \sim 10^{17} - 10^{18}$ K in regions

where $v_b \geq 5 \times 10^6 \text{ m s}^{-1}$. Figure 2 shows these wave levels are consistent with those predicted by extrapolating the observed Langmuir wave levels in planetary foreshocks to outer heliospheric distances. These Langmuir wave levels should be easily observable by the plasma wave instruments on the Voyager spacecraft.

Figure 2 shows that Langmuir waves having field strengths in the range $1 - 10^4 \mu\text{V m}^{-1}$ are observed in planetary foreshocks. Rearranging equation (13) to give T_L as a function of E_L and the plasma and beam parameters, the ranges of T_L for the Langmuir waves observed in the foreshocks of Earth and the outer planets are given in Table 1. These calculated values use the observed electric fields (Figure 2) and local plasma frequencies in these foreshocks (courtesy of S. L. Moses), and the beam parameters $\Delta\Omega_L = 0.1 - 1$, $\Delta k_L/k_L = 0.1 - 1$, and $5 \times 10^6 \leq v_b \leq 5 \times 10^7 \text{ m s}^{-1}$. Table 1 shows that (1) the observed foreshock waves easily span the range $10^{17} - 10^{18}$ K for likely beam parameters and (2) Langmuir waves in an outer heliospheric source, especially a foreshocklike source as suggested by *Macek et al.* [1991a,b] and *Cairns et al.* [this issue], will plausibly have T_L in the range $10^{17} - 10^{18}$ K, and possibly $T_L \sim 10^{20}$ K under optimum conditions.

TABLE 1. Effective Langmuir Wave Temperatures

	Earth	Jupiter	Saturn	Uranus	Neptune
f_p , kHz	28	6.4	3	2	0.6
T_L , K	5×10^{11}	10^{12}	3×10^{13}	6×10^{12}	10^{14}
to	to	to	to	to	to
10^{19}	3×10^{19}	10^{20}	3×10^{20}	3×10^{20}	3×10^{20}

Electron beams can, in principle, easily provide sufficient free energy for even higher field strengths. Supposing that a fraction η of a beam's kinetic energy goes into wave energy, the electric field E_L is then given by

$$E_L^2 = \eta \frac{n_b}{n_0} v_b^2 \frac{n_0 m_e}{\epsilon_0} \quad (18)$$

Here n_b/n_0 is the relative beam number density. With $f_p = 1.5$ kHz, this equation implies

$$E_L \sim 0.5 \frac{v_b}{10^7} \left(\frac{n_b}{n_0}\right)^{1/2} \text{ V m}^{-1} \quad (19)$$

The maximum theoretical value for η is $\frac{2}{3}$, corresponding to homogeneous quasi-linear relaxation of the beam. Field strengths in excess of $50 \mu\text{V m}^{-1}$ may be obtained for wide ranges of values for η , n_b/n_0 and v_b . In particular, for n_b/n_0 in the range $10^{-4} - 10^{-2}$ and beam speeds $v_b \sim 10^7 \text{ m s}^{-1}$, field strengths of order $50 \mu\text{V m}^{-1}$ correspond to values $\eta \sim 10^{-6} - 10^{-4}$. Larger beam speeds permit smaller values of η for the same field strength E_L (or temperature T_L) and relative beam density.

The ratio $w = W_L/n_e k_B T_e$ of electric field energy density to thermal plasma density is an important parameter in determining whether the Langmuir waves are subject to strong turbulence processes such as collapse of wave packets and modulational instability [e.g., *Goldman*, 1984]. Using the parameters for equation (17), $T_e = 10^4$ K, and SI units for T_L and v_b , one finds

$$w = 4 \times 10^{-2} \frac{T_L}{v_b^3} \quad (20)$$

Thus, for $T_L = 10^{17}$ K and $v_b = 10^7$ m s⁻¹, the relative energy density $w = 4 \times 10^{-6}$. Smaller beam speeds imply larger ratios w for the same T_L . In comparison, the threshold [Papadopoulos *et al.*, 1974] for the conventional modulational instability is $w > (k_L \lambda_e^2) \sim (V_e/v_b)^2$, where λ_e is the Debye length. The above ranges of wave and beam parameters indicate that this threshold is not likely to be attained unless $T_L \geq 10^{20}$ K. The threshold for the nucleation instability route toward collapse is lower than that for the modulational instability route [Robinson and Newman, 1991]: $w \geq 7 w_{\text{rms}}$ where w_{rms} is the root-mean-square value of the ratio of field energy to thermal plasma energy. This threshold implies that collapse will almost invariably be important for some wave packets in a plasma. However, the time taken for a wave packet to collapse is then estimated to be $t_c = 36/(\omega_p w_{\text{rms}})$. For $w_{\text{rms}} = 4 \times 10^{-6}$, as calculated using equation (20) with $T_L = 10^{17}$ K and $v_b = 10^7$ m s⁻¹, the collapse time is $t_c \sim 1000$ s. Thus, in view of the observational uncertainty of whether collapse occurs in planetary foreshocks and the long calculated time scale for collapse, we shall not consider strong turbulence processes further here. We recognize that collapsing wave packets may generate f_p and $2f_p$ radiation more efficiently than the weak turbulence processes considered here. This will strengthen our conclusion below and elsewhere [Cairns *et al.*, this issue] that the 2- to 3-kHz radio emissions can be generated at multiples of f_p .

6. DISCUSSION OF SOURCE MODELS

The high brightness temperature of the observed radio emissions requires highly nonthermal levels of Langmuir waves for a theory in terms of radiation at multiples of f_p to be viable. In particular, as argued in section 3 using general theoretical limits on T_L , the observed brightness temperatures rule out thermal and known stable sources for the Langmuir waves. Instabilities are the only known source of such highly nonthermal levels of Langmuir waves, and the most plausible instability is the ordinary electron beam instability. The beam instability can generate the levels of Langmuir waves required to produce the observed levels of radiation in path lengths less than or of the order of 1 AU. Larger path lengths (and presumably source dimensions) imply smaller Langmuir wave levels for the same level of radiation and vice versa. However, producing the Langmuir waves by the beam instability requires that the radiation source lie in the vicinity of an electron acceleration region capable of producing electron beams. This is an important further constraint on source models for the radiation. We refer the interested reader to the original works of Kurth *et al.* [1984, 1986, 1987] for discussion of possible sources such as Jupiter and Saturn and emission mechanisms different from radiation at multiples of f_p .

Kurth *et al.* [1987] argued against the radiation having an extended source in the solar wind at heliocentric distances of order 5–15 AU where the solar wind plasma frequency is in the range 1–3 kHz. Kurth *et al.*'s primary argument is that the Voyager spacecraft did not observe suitable Langmuir waves in this volume of space, not even upstream from traveling interplanetary shocks. There are at least two further arguments against this possibility. First, any Langmuir waves below the

Voyager detection threshold in this region cannot satisfy either the constraint that $T_L \geq T$ or the constraint that the required path length be small compared with 1–10 AU. Second, neither observational evidence nor theoretical models exist for large-scale electron beam production and growth of intense Langmuir waves in the required region of space. There is an implicit assumption in the above arguments involving observational data: that the source region is sufficiently large and long-lived for the Voyager spacecraft to have reasonably sampled it. Accordingly, the above arguments do not necessarily rule out an inner heliospheric source for the radiation provided that a theoretical model can be developed for a large-scale (~ 1 AU), time-variable region with intense Langmuir waves not reasonably sampled by the Voyager spacecraft. At the present time no suitable model is available; however, a collaboration involving ourselves, C. K. Goertz, and W. S. Kurth is currently investigating the possibility of unusual electron production events at Jupiter and/or Saturn leading to type III-like radio emissions potentially similar to the observed emissions.

The source for the radiation has also been suggested to be the downstream side of the inner (or termination) heliospheric shock [Kurth *et al.*, 1984] and the near vicinity of the heliopause [Fahr *et al.*, 1986]. These source regions are attractive in that the plasma frequency in the source (and so wave frequencies) should be substantially larger than the solar wind plasma frequency, thereby apparently alleviating theoretical difficulties in positioning the shock-heliopause system. In addition, these sources may naturally extend many astronomical units. However, these source locations also encounter substantial theoretical and observational difficulties, as is now shown. The primary problem follows from the (apparently) universal expectation [e.g., Fahr *et al.*, 1986] that the sunward (upstream) side of the inner heliospheric shock is the low-density, low magnetic field side. Accordingly, both by analogy with planetary bow shocks and by consideration of specific acceleration and reflection mechanisms, electron acceleration is expected on the upstream side and not the downstream side of the inner shock [Macek *et al.*, 1991a]. Energetic electron beams and accompanying intense Langmuir waves should then be found in a foreshock region upstream (sunward) of the inner heliospheric shock. In contrast, no theoretical reason for electron acceleration and growth of Langmuir waves is apparent for the downstream side of the inner shock, thereby arguing against a downstream source for the radiation. Furthermore, the magnetosheaths of the outer planets (expected to be analogous to the downstream side of the inner shock) show extremely low levels of waves, and in particular no Langmuir waves [e.g., Gurnett *et al.*, 1989; Moses *et al.*, 1990; and references therein]. The absence of an electron acceleration mechanism and the very low levels of Langmuir waves expected therefore argue against the radiation source being on the downstream side of the inner heliospheric shock.

Similar problems exist for source locations near the heliopause. First, electron acceleration and beam production are not familiar phenomena at planetary magnetopauses, thereby forming a significant theoretical difficulty for this hypothesis. Second, high levels of Langmuir waves are not observed near the magnetopauses of the outer planets [e.g., Moses *et al.*, 1990, and references therein]. Although magnetic reconnection may occur at the heliopause [Fahr *et al.*, 1986], as at planetary

magnetopauses, and may in principle produce streaming electrons and associated Langmuir waves, there is no known reason for this process to be more important at the heliopause than at planetary magnetopauses. Thus, based on present knowledge of planetary magnetosheaths and present predictions for the characteristics of the heliopause, there are severe theoretical and observational problems with the radiation being produced by beam-driven Langmuir waves in the vicinity of the heliopause. In passing we note that mode conversion of upper hybrid waves at density gradients near the heliopause remains a possible origin for the observed radio emissions; similar models have been envisaged for some components of continuum radiation in the magnetospheres of Earth, Jupiter, and Saturn (see, for example, Figure 7 of Gurnett *et al.* [1983] and the review by Anderson and Kurth [1989]). This possibility is not discussed further here.

The arguments sketched above and considered in detail by Macek *et al.* [1991a] and Cairns *et al.* [this issue] suggest that electron acceleration and growth of Langmuir waves takes place in a foreshock region sunward of the inner heliospheric shock. This model is directly analogous to the accepted theory at Earth [Scarf *et al.*, 1971; Filbert and Kellogg, 1979; Cairns, 1987b; Fitzenreiter *et al.*, 1990]. The existence of a foreshock sunward of the inner heliospheric shock therefore has substantial theoretical support and is consistent with the Voyager observations of foreshocks containing significant levels of Langmuir waves upstream from the bow shocks of all the outer planets. Elsewhere [Macek *et al.*, 1991a,b; Cairns *et al.*, this issue] we suggest that the observed outer heliospheric radio emissions may be generated in a region of this foreshock containing intense Langmuir waves. This source region then naturally provides high levels of beam-driven Langmuir waves. Furthermore, the calculations in sections 4 and 5 indicate that there is no theoretical problem in this foreshock containing intense enough Langmuir waves ($T_L \sim 10^{17}$ K) to produce f_p and $2f_p$ radiation with the observed brightness temperatures in distances small compared with the predicted foreshock dimensions [Cairns *et al.*, this issue]. Much higher Langmuir wave levels are required for production of observable $3f_p$ radiation in these path lengths; this constitutes a major potential problem for theories interpreting the 3-kHz radiation as $3f_p$ radiation. A detailed discussion of the proposed foreshock source is given in the companion paper [Cairns *et al.*, this issue].

7. CONCLUDING REMARKS AND SUMMARY

We have considered constraints on the emission mechanisms and source characteristics of the outer heliospheric radio emissions assuming only that the radiation is generated at multiples of the plasma frequency f_p by nonlinear processes involving Langmuir waves. While at the present time no other viable interpretation for the radiation exists, there is currently no definitive proof that the observed radio emissions are generated at multiples of f_p in the outer heliosphere. However, the theoretical analyses in this paper demonstrate quantitatively for the first time the plausibility of the observed radiation being f_p and/or $2f_p$ radiation generated in the outer heliosphere. In addition, the analyses performed here demonstrate that only one proposed outer heliospheric source remains viable for the radiation: the foreshock region predicted sunward of the inner heliospheric shock [Macek *et al.*, 1991a,b; Cairns *et al.*, this issue].

Estimates of the brightness temperature and volume emissivity of the radiation fall into the range spanned by other known solar system sources of f_p and $2f_p$ radiation. The brightness temperature of the radiation constrains the effective temperature T_L of the Langmuir waves to be greater than 3×10^{14} K. This requires highly nonthermal levels of Langmuir waves to be present in the source and rules out generation of the radiation by thermal and known stable sources of Langmuir waves. Two-stream instabilities driven by electron beams are the only plausible source of such high levels of Langmuir waves; this requires a large-scale electron acceleration region in the near vicinity of the radiation source. Calculations for the path length of radiation generated by specific f_p , $2f_p$, and $3f_p$ emission processes constrain the levels T_L and E_L required to produce the observed levels of radiation in specified distances. Nominal plasma and beam parameters imply that Langmuir waves with $T_L \sim 10^{17}$ K could produce the observed levels of both f_p and $2f_p$ radiation in distances of order 1 AU or less. Langmuir wave levels of order 10^{22} K are required for production of equivalent levels of $3f_p$ radiation in the same distances. Smaller path lengths for the same level of radiation require larger T_L or smaller beam speeds v_b in the source region. Extrapolations of the Langmuir levels observed in planetary foreshocks to an outer heliospheric source suggest no difficulty, in principle, in obtaining large Langmuir wave levels with $T_L \sim 10^{17}$ K (Table 1). Similarly, electron beams with characteristics typical of space plasmas (i.e., $n_b/n_0 \sim 10^{-4}-10^{-2}$ and $v_b \sim 10^7$ m s $^{-1}$) have adequate free energy to produce such wave levels even if only $10^{-4}-10^{-2}\%$ of the free energy is transformed into wave energy. Production of Langmuir waves with $T_L \sim 10^{22}$ K, while possible in principle, is relatively implausible.

These results constrain the source of the observed radio emissions. Arguments against a distributed source for the radiation in the inner heliosphere (~ 15 AU) where $f_p \sim 2-3$ kHz include the observed lack of suitable Langmuir waves and the lack of a suitable theoretical electron acceleration (and Langmuir wave production) region. Kurth *et al.*'s [1984] suggestion that the radiation source is on the downstream side of the inner heliospheric shock is not viable, on the basis of present understanding of the heliospheric shock system, because of (1) the theoretical absence of a region of electron acceleration and suitably nonthermal Langmuir wave production on the downstream side of the shock, and (2) the observed lack of suitable Langmuir waves in the magnetosheaths of the outer planets. Essentially identical arguments rule out, based on present knowledge, Fahr *et al.*'s [1986] suggestion that the radiation source is in the near vicinity of the heliopause.

In contrast to these models, the foreshock region [Macek *et al.*, 1991a] sunward of the inner heliospheric shock remains a potentially viable source region for radiation at multiples of f_p . Indeed, the Langmuir wave levels predicted by either extrapolating the levels observed in planetary foreshocks or theoretical calculations are sufficient (i.e., $T_L \sim 10^{17}$ K) to generate the observed level of radio emissions at f_p and $2f_p$ in distances small compared with 1 AU. These path lengths are consistent with the predicted foreshock dimensions [Cairns *et al.*, this issue]. A detailed discussion of the strengths and weaknesses of this source model for the radiation is presented by Cairns *et al.* [this issue].

In conclusion, we have shown quantitatively that the observed outer heliospheric radio emissions can plausibly be f_p and $2f_p$ radiation generated in the outer heliosphere. A plausible source region is the foreshock predicted sunward of the inner heliospheric shock. The Voyager 1 spacecraft is traveling in the approximate direction of this expected foreshock region. Since Voyager 1 should reach a heliocentric distance of 50 AU in 1992 and 100 AU in 2006, it is possible that in situ testing of the theory presented here and in the companion paper will be possible in the foreseeable future.

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