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PLASMA WAVE GENERATION NEAR THE INNER HELIOSPHERIC SHOCK

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Abstract. There is mounting evidence that the Voyager 1 and 2 and Pioneer 11 spacecraft may approach the inner (termination) heliospheric shock near the end of this century. It is argued here, by analogy with planetary bow shocks, that energetic electrons backstreaming from the heliospheric shock along the magnetic field should be unstable to the generation of Langmuir waves by the electron beam instability. Analytic expressions for the cutoff velocity, corresponding to the beam speed of the electrons backstreaming from the shock, are derived for a standard solar wind model. At the front side of the heliosphere the maximum beam velocity is expected to be at the meridian passing through the nose of the shock, which is assumed aligned with the Very Local Inter-Stellar Medium (VLISM) flow. This foreshock region and the associated Langmuir waves are relevant to both the expected *in situ* observations of the heliospheric boundaries, and to the low-frequency (2-3 kHz) radio emissions observed by the Voyager spacecraft in the outer heliosphere. Provided that these radio emissions are generated by Langmuir waves, the minimum Langmuir wave electric fields at the remote source are estimated to be ≥ 3 - 30 μV/m.

Introduction

The interaction between the supersonic solar wind plasma and the ionized component of the VLISM 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, 1990; Suess, 1990].

The Voyager 1 and 2 and Pioneer 11 spacecraft are moving toward the front side of the inner heliospheric shock. Discussion of the plasma waves expected near the heliospheric boundaries is therefore of considerable interest. Moreover, during the interval 1983-1987, Voyagers 1 and 2 at radial distances (from the Sun) of $r \geq 17$ AU and 13 AU, respectively, observed radio emissions [Kurth et al., 1984, 1986, 1987; Kurth, 1990] at low frequencies $f \sim 2$ and 3 kHz. These emissions are above the local fundamental electron plasma frequency f_p [Kurth et al., 1984] and show an upward drift in frequency at a rate $\sim$ 1 kHz/yr [Kurth et al., 1987; Czechowski and Grzedzielski, 1990]. Possible sources include electromagnetic radiation generated at multiples of f_p near and/or reflected from either the inner heliospheric shock [Kurth et al., 1984, 1987] or the heliopause [Fahr et al., 1986]. Both these interpretations for the radio emissions and also 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 ($r \sim 50$ AU) solar wind shock.

In this paper we present a simple analytic model for the generation mechanism of Langmuir waves sunward of the inner heliospheric shock. The model is directly analogous to the current model at Earth [Filbert and Kellogg, 1979; Cairns, 1987a, b] and provides a quantitative explanation for the remote observations of radio emissions in the outer heliosphere. We also discuss the relevance of these ideas to possible direct observations of the heliospheric boundaries.

Model

Consider a plasma with magnetic field $\mathbf{B}$ and a flow velocity $\mathbf{v}$. The presence of a convection electric field $-\mathbf{v} \times \mathbf{B}$ causes the gyrocenters of all particles to drift with the same velocity $\mathbf{v}_d = -(\mathbf{v} \times \hat{\mathbf{B}}) \times \hat{\mathbf{B}} = \mathbf{v} - (\mathbf{v} \cdot \hat{\mathbf{B}})\, \hat{\mathbf{B}}$ in the direction perpendicular to a unit vector $\hat{\mathbf{B}}$, which is locally tangential to the magnetic field line. Additionally, an individual particle can have a component $v_\parallel$ of the velocity along $\hat{\mathbf{B}}$. Figure 1 shows the geometry assumed for charged particles backstreaming from a stationary shock. At any point P of a given shock surface, the unit normal vector $\hat{\mathbf{n}}$ does not lie, generally, in the plane determined by $\mathbf{v}$ and $\hat{\mathbf{B}}$. Namely, three vectors $\mathbf{v}$, $(\mathbf{v} \cdot \hat{\mathbf{n}})\, \hat{\mathbf{n}}$, and $[(\mathbf{v} \cdot \hat{\mathbf{n}})/(\hat{\mathbf{B}} \cdot \hat{\mathbf{n}})]\, \hat{\mathbf{B}}$ outgoing from P determine a right angle pyramid with a base (opposite to P, shown hatched) parallel to the plane tangential to the shock surface. In the shock rest frame, this means that a particle with $v_\parallel = v_c = |(\mathbf{v} \cdot \hat{\mathbf{n}})/(\hat{\mathbf{B}} \cdot \hat{\mathbf{n}}) - (\mathbf{v} \cdot \hat{\mathbf{B}})|$ moves parallel to the local shock surface. Escape of particles from

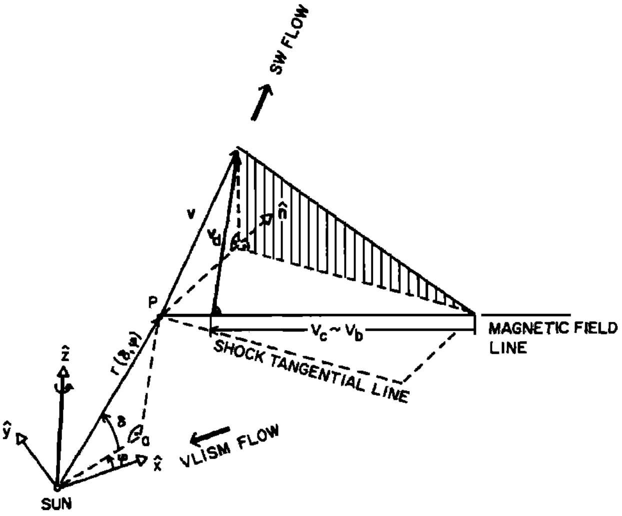

Fig. 1. Adopted geometry of the heliospheric boundary between the solar wind (SW) and the Very Local Inter-Stellar Medium (VLISM) flows. The hatched surface is parallel to the local inner shock surface.

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the local shock surface requires that the particle paths lie upstream of the shock surface, thereby placing a lower limit on $v_{\parallel}$ at $v_{\parallel} = v_c$.

The so-called cutoff speed v_c [Filbert and Kellogg, 1979; Cairns, 1987a, b] is critical to the theory of beam-plasma interaction. A streaming instability tends to erode the sharp cutoff feature at v_c and forms a smooth beam distribution of velocities near $v_b \sim v_c$. In effect, v_c can be identified approximately with an average speed v_b of the beam electrons streaming along $\hat{\mathbf{B}}$.

We apply this general idea for beam formation to the heliospheric case, adopting the geometry shown in Figure 1. For simplicity the VLISM flow is taken to be parallel with a constant pressure Π^{VLISM}. The plasma apex ("head-on" direction of the VLISM velocity: $\hat{v}^{VLISM} = -\hat{x}$) is assumed to be located in the solar equatorial ($\hat{x}$, $\hat{y}$) plane (SEP) and is taken to be the $\hat{x}$-axis ($\delta = 0°$, $\varphi = 0°$). Here δ and φ (measured from the $\hat{x}$-axis in the direction of solar rotation) are the latitude and longitude defined with respect to the SEP. Spherical symmetry for the solar wind is adopted. Accordingly, the solar wind has a radial flow velocity ($\hat{v}=\hat{r}$) and for $r \gg r_E = 1$ AU its total pressure is $\Pi \sim \Pi(r_E) (r_E/r)^2$. However, the solar wind magnetic field should have a symmetry with respect to the $\hat{z}$-axis of solar rotation. As a consequence of the solar angular velocity and the average solar wind speed, the radial $B_r \propto 1/r^2$ and azimuthal $B_\varphi \propto 1/r$ components of the solar wind magnetic field can be taken as equal at $r = r_E$. In a standard model [Parker, 1963] the magnetic field lines are spirals wound up on conical surfaces: $\hat{\mathbf{B}} = \pm (\hat{r} - a\,\hat{\varphi})/(1 + a^2)^{1/2}$, where $a = (r/r_E) \cos \delta$ is the distance to the $\hat{z}$-axis. The plus and minus signs denote outward and inward polarity, respectively. Hence, for an arbitrary shock shape $r = r(\delta, \varphi)$ with $H = \partial (r/r_E)/\partial\varphi$ one finds

$$v_b / v = (1 + a^2)^{1/2} / (1 + H) - 1 / (1 + a^2)^{1/2} \qquad (1)$$

Pressure balance in the Newtonian approximation, as usually applied for the magnetospheric boundaries, can determine the shape $r(\delta, \varphi)$ of the heliospheric boundary. Its "nose" location is assumed to be on the $\hat{x}$-axis at a distance $D = r_E (\Pi(r_E)/\Pi^{VLISM})^{1/2}$ [e.g., Parker, 1963]. Taking into account only ram pressures (for initially super-sonic flows) the shape is simply [Macek, 1989, 1990] $r/D = \alpha/\sin \alpha$, where α is defined by $\cos\alpha = \hat{r} \cdot \hat{x} = \cos\delta \cos\varphi$. This shock shape can be approximated by a paraboloid: $X/D + (Y^2 + Z^2)/(\pi D/2)^2 = 1$, and on the front side (i.e., for $\alpha \leq 90°$, at $\alpha = 90°$ $r/D = \pi/2$) even better (with accuracy $\leq 1\%$) by an ellipsoid with a focus at the Sun, and an eccentricity equal to $\pi/2 - 1$. We note that the more rigorous hydrodynamic simulations of all heliospheric boundaries [Baranov, 1990] show that the shapes of the heliopause and the inner shock are similar and both are well fitted by our shape. It could play, heuristically, the same role as the paraboloidal shape usually adopted for planetary shocks. For now, we identify our shape with the inner heliospheric shock on its front side, $\alpha \leq 90°$ (the tail region $\alpha > 90°$ is not considered here). The shape adopted here is symmetric with respect to the $\hat{x}$-axis. Defining an angle ξ by $\cos \xi = \hat{n} \cdot \hat{r}$, one obtains $H = a (\sin \varphi/\sin \alpha) \tan \xi$, with $\tan \xi = 1/\alpha - 1/\tan \alpha$ in equation (1).

The beam speed v_b, in units of solar wind flow velocity v, calculated for the foregoing model is now presented in Figure 2 as a function of δ and φ (for $\delta \leq 90°$, $\varphi \leq 90°$). This speed reaches its minimum value $v_b = 0$ ($a = 0$) when $\delta \simeq 90°$. However, very large beam speeds are found on the meridian ($\varphi = 0°$) passing through the nose of the shock except where $\delta \simeq 90°$. The maximum beam speed is at the nose v_b ($\delta = 0°$, $\varphi = 0°$) $= v\,(D/r_E)^2/[1+(D/r_E)^2]^{1/2} \approx v\,(D/r_E)$ (for $D \gg r_E$). Accordingly, the maximum beam speed depends directly on the size of the heliospheric cavity. The value of D is still the subject of conjecture. Commonly quoted values [e.g., Axford, 1973; McNutt, 1988; Czechowski and Grzedzielski, 1990; Kurth, 1990; Suess, 1990] are in the range $D/r_E = 50 - 150$.

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 strength [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 v_b is large.

Now, given the beam of electrons, the generation mechanism of the radiation is described in two steps. First, as is well known from studies of quasi-perpendicular planetary bow shocks [Gurnett, 1975; Filbert and Kellogg, 1979; Melrose, 1980; Cairns, 1987a, b, 1988], electrons energized at regions of the shock where v_b is large generate high levels of electrostatic Langmuir plasma waves. Thus, electron beams should produce Langmuir waves near the heliospheric shock. We assume that the beam speed v_b is approximately equal to the phase speed of the Langmuir waves. They are concentrated near a wave vector $(2\pi/\lambda)\,\hat{v}_b$, where $\hat{v}_b \sim \hat{\mathbf{B}}$ and their wavelengths $\lambda = v_b/f_p$ [Cairns and Melrose, 1985] depend on the corresponding local electron plasma density n_e. The almost tangential magnetic field should severely limit the radial extent of the Langmuir wave

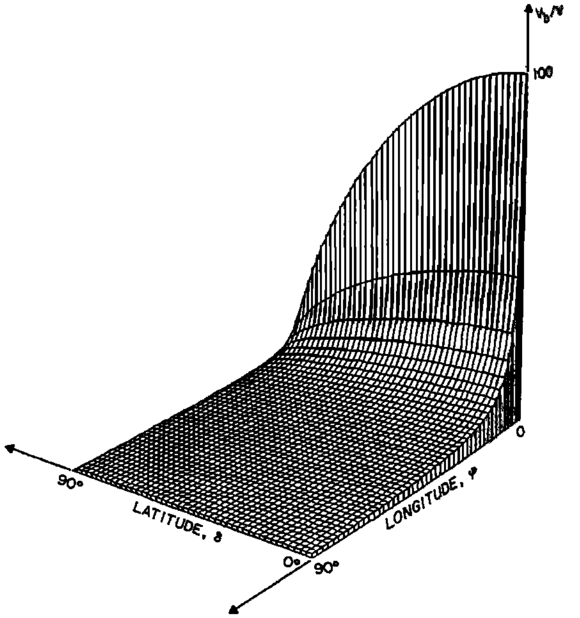

Fig. 2. Predicted average speed v_b of electrons streaming along the magnetic field in units of solar wind flow velocity v (equation (1)) as a function of the heliospheric latitude δ and longitude φ (D = 100 AU is taken).

source region. Nevertheless, a large source is expected [Macek et al., 1990]. For $2f_p \sim 3$ kHz one has $n_e \sim 0.028$ cm^{-3} (or a sunward solar wind density of ~ 0.007 cm^{-3}) [Kurth et al., 1984]. Taking $v = 450$ km s^{-1} = 0.0015 c (where c is the velocity of light) in equation (1) and $D/r_B = 100$ (Figure 2), one finds $v_b \sim 0.15$ c (~ 6 keV) near the nose of the heliospheric shock. The resulting Langmuir wavelength is then $\lambda \sim 30$ km. Taking an electron temperature as 2 eV [Burlaga et al., 1990, equation (5)] one expects a Debye length of $\sim 10^2$ m ($\ll 30$ km) in the outer heliosphere. Hence, it is likely that the Langmuir waves in the source should be only weakly damped. Also magnetosheath electron temperatures (< 50 eV) seen by Voyager at Uranus and Neptune support this conclusion.

Second, electromagnetic radiation able to leave the source region can result from the interaction between Langmuir waves in a source due to nonlinear processes considered by Macek et al. [1990]. Therefore, this naturally occurring radiation can be observed remotely from the radiation source.

For a given solid angle Ω_s subtended by a remote source from a point of observation the measured power per unit area per unit frequency interval, i.e., the flux density F, implies a brightness temperature of the source $T_{eff} = c^2F/(2\,\kappa\, f^2\, \Omega_s)$, where κ is Boltzmann's constant, providing the most information about the remote source [Melrose, 1980]. The measured $F \approx 10^{-17}$ W m^{-2} Hz^{-1} [Kurth et al., 1984] (for $\Omega_s \leq \pi$ sr) implies $T_{eff} \geq 10^{15}$ K. These temperatures are comparable to those for the most intense type III solar radio bursts and are much larger than for the $2f_p$ radiation generated near the Earth's bow shock. The fact that T_{eff} is so high ($\gg m_e c^2/\kappa$, m_e is the electron mass) shows that the radiation is *not* thermal [Macek et al., 1990].

For radiation generated at multiples of f_p by nonlinear processes involving Langmuir waves [Melrose, 1980; Cairns and Melrose, 1985] we can estimate the minimum wave electric field E^L required in the source by assuming saturation of the emission processes. For $2f_p$ emission from two Langmuir waves, kinematic constraints [Macek et al., 1990, equation (4)] then give

$$F \approx \zeta\,(6c/f_p)\,(v_b/c)^3\,\epsilon_0 (E^L)^2 \qquad (2)$$

Here $\zeta = (\Omega_s/\Delta\Omega)/|\Delta\lambda/\lambda|$, where $|\Delta\lambda/\lambda|$ is a relative bandwidth (usually not very large) of Langmuir plasma waves and $\Delta\Omega$ is their range of propagation solid angles (ϵ_0 is the permittivity of free space).

The observed flux density F, nominal source parameters: $2f_p \sim 3$ kHz, $v_b \sim 0.15$ c, $|\Delta\lambda/\lambda| = 0.1 - 1.0$, $\Delta\Omega = 0.1 - 1.0$ sr, and a source size of $\Omega_s \sim 0.1\,\pi$ sr (resulting from Figure 2 and taken in equation (2)) then imply a minimum 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 [Macek et al., 1990].

Discussion

It is necessary to mention the limitations of the analytic model adopted here for numerical illustration of the main idea of this paper. Whether the magnetic fields at the boundaries of the solar system are sufficiently regular to justify our simple description remains an open question. The actual flow pattern of the solar wind and its magnetic field geometry may differ from those assumed in this paper. However, because the symmetries adopted here should be approximately satisfied, we expect that our main conclusions are not strongly sensitive to the shape of the shock surface or on the details of the magnetic field at that surface. Deflections of the apex from the solar equator and the nose from the apex are not considered here. An additional complication to this picture is the temporal variability of the shock [McNutt, 1988; Lazarus and McNutt, 1990].

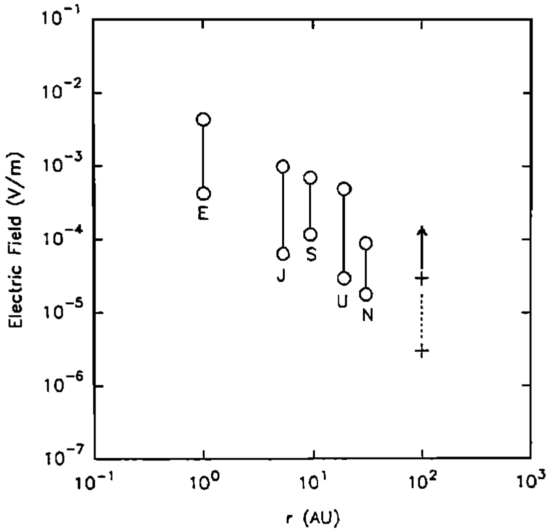

Fig. 3. Comparison of the electric field of electron plasma oscillations measured near planetary bow shocks at Earth (E), Jupiter (J), Saturn (S), Uranus (U), and Neptune (N) (solid bars, Gurnett et al., 1989). The minimum average field strength of the Langmuir wave in the outer heliosphere, as calculated here, is shown by a dotted bar.

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 ~ 50 AU in 1992 and r ~ 100 AU in 2006. After Neptune Voyager 2 is traveling ~ 45° 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 the flux density given by equation (2) 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 v_b is calculated to be large, and so a likely source region for Langmuir waves. However, the Voyager 1 and 2 spacecraft will not have enough power to operate beyond the year 2017, when they will be at r ~ 138 AU and r ~ 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.

Until now, with the Voyager spacecraft still located far from the Langmuir wave source region, only escaping electromagnetic radiation may have been detected as argued by Kurth et al. [1984, 1987]. In contrast, Meyer-Vernet [1989] suggests that the observed signals could be a phenomenon local to the spacecraft. The present paper, while providing no direct arguments against this idea, gives direct support for the interpretation by Kurth et al. [1984, 1987] and recently by Kurth and Gurnett [submitted to *Astron. Astrophys.*, 1990] due to our identification of a suitable source region for the radiation.

In conclusion, we have shown that electrons backstreaming from the region where the magnetic field is nearly tangential to the termination heliospheric shock should have a beam-like velocity distribution and should drive Langmuir plasma waves by the standard electron beam instability. These waves may produce high levels of radiation at multiples of the plasma frequency.

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