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LETTER

Letter to the Editor

Heliopause radio emission scenario

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Abstract. Heliospheric (HSP) radio emission detected by the Voyager spacecraft between 1.8 kHz and 3.6 kHz from the distant heliosphere is interpreted as emission generated close to and at the heliopause (HP), the interface between the ionised very local interstellar (LIC) gas and the supersonic solar wind (SW) stream. Radio emission is assumed to be triggered by secondary charge exchange ionisation of interstellar neutrals and subsequent generation of lower hybrid (LH) waves. These waves nonlinearly accelerate electrons into beams along the spiral compressed heliosheath (HS) magnetic field $\mathbf{B}$. Langmuir waves locally generated by these beams may be responsible for the observed emission. Under quiet conditions the emission is at marginally high frequency for observation. Under disturbed conditions the plasma density may be high enough to explain the Voyager observations. In this mechanism $\mathbf{B}$ plays a crucial role.

Key words: distant heliosphere – heliopause and termination shock – radio emission mechanism

1. Introduction

Distant HSP radio emission in the frequency band $1 < f < 4$ kHz (Kurth et al., 1984, Gurnett et al. 1993) has been interpreted as either being generated at the HSP terminal shock (TS) (Macek et al. 1991, Cairns et al. 1992) or at the heliopause (HP) (Fahr et al. 1986, Gurnett et al. 1993). The latter possibility seems particularly interesting in view of a number of observational properties like the updrift in frequency of the emission at the small rate of roughly 3 kHz/yr (Gurnett et al. 1993). This drift has been interpreted as either monitoring the density profile of the HP or as hypothetical Fermi-Doppler shift of radiation trapped between travelling density pulses or shocks and the HP (Czechowski and Grzedzielski 1990, Cairns et al. 1992, Czechowski et al. 1995). HP interface radiation mechanisms have been suggested by Fahr and Neutsch (1983) and Fahr (1993). In sharp contrast, planetary magnetopauses and ionopauses do not exhibit similar radio emissions. The proposed HP emission seems to be the strongest radio source in the entire HSP (Gurnett et al. 1993) with the exception of the Sun itself. Here we propose another simple mechanism which could be capable of generating radio waves in the exceptional case of the HP.

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2. Properties of the heliopause

The HP as the transition region from the fast cool SW to the cold weakly ionised very local interstellar gas cloud (LIC) is a relatively diffuse boundary having complex properties (for an early account see Fahr and Neutsch 1983). Its formation has been studied with the help of kinetic simulations of the interaction between the gases involved (cf., e.g., Baranov and Malama 1996, Chalov and Fahr 1997) and recently also in MHD simulations (e.g., Linde et al. 1998) assuming a Parker spiral interplanetary magnetic field configuration. The main interaction process between the LIC gas and the SW ions has been identified as charge exchange over a distance which is roughly of the order of about 100 AU. In the course of charge exchange and subsequent pressure and momentum balance between the SW and LIC ions, the HP is a relatively sharp boundary whose width is of the order of ~ 20 AU. In the head-on interaction region the interstellar ions pile up to form an overdense wall. The density increase is by a factor of $\sim$2 from about $0.07 \rightarrow 0.15\,\mathrm{cm}^{-3}$.

Fig. 1 shows the density profile (dashed curve) in the vicinity of the HP as obtained from (non-magnetised) kinetic simulations (Izmodenov et al. 1998). This figure includes the densities of the neutral hydrogen beam generated by charge exchange between neutral interstellar gas and the SW deep in the HSP. This hydrogen beam propagates radially outward with SW speed and, when passing close to the HP, undergoes a secondary charge exchange that leads to re-ionisation. In the SW this re-ionisation is unimportant, but neutrals are not affected by the TS. Hence, re-ionised neutrals become important *behind* the TS in the HS because of their much higher than flow speed radial velocity. Their density reaches a fraction of 3×10^{-4} of the local slow, thermalised HS plasma. Close to the HP this plasma is diverted into tangential direction while the full speed of the newly created ions stays radial.

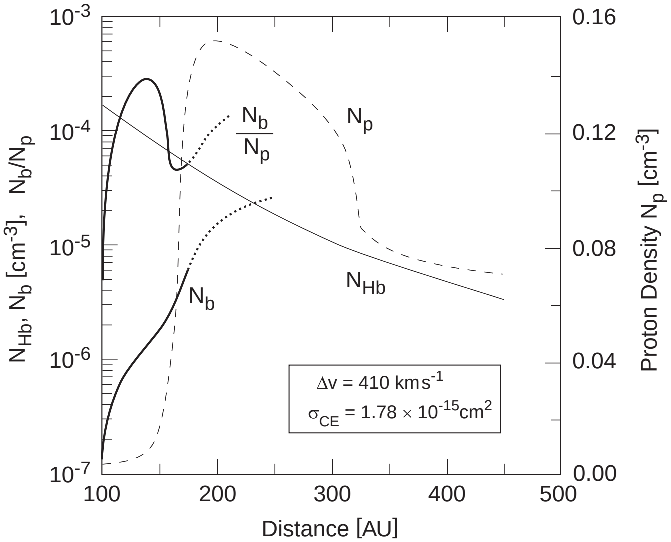

Fig. 1. Density profiles across the upwind HP behind the TS. Proton density $N_{\rm p}$ (right scale) resulting from charge exchange with cross-section σ_{CE} for an average SW velocity of 410 km s^{-1}. $N_{{\rm H}b}$ and $N_{\rm b}$ (left scale) refer to the density of the fast neutral hydrogen beam produced in inner HSP charge exchange interaction and to the density of the fast proton beam produced behind the TS by secondary (reverse) charge exchange. $N_{\rm b}/N_{\rm p}$ (left scale) is the ratio of secondary beam to proton density. This is highest in the HS between TS and HP.

Little is known about the direction and strength of $\mathbf{B}$ in the HS. MHD simulations assume that $\mathbf{B}$ has the Parker spiral structure being azimuthal at these distances. The deviation of the field from the azimuthal direction is believed to be of the order of $\sim 1^\circ$. In a nearly azimuthal geometry, the field in the upwind region will be compressed by up to a factor 4 across the TS. Any newly created ion in the HS moving radially out turns its motion into a gyration around the compressed $\mathbf{B}$ with gyroradius $r_{{\rm c}i} \approx 10^2 - 10^3\,{\rm km} \ll 1$ AU. In the HS $\mathbf{B}$ field they like pick-up ions form a ring beam distribution. Over scales $r < r_{{\rm c}i}$ the non-neutralised ions generate charge-neutralising electron currents to flow along $\mathbf{B}$. Their bulk flow velocities $v_{\rm D}$ range between the Alfvén speed and the thermal electron velocity, $v_{\rm A} < v_{\rm D} < v_{\rm e}$ and are thus high enough to drive plasma instabilities. Here plasma waves ranging from Alfvén, mirror, and slow to Langmuir modes will be excited at all frequencies by temperature anisotropies and other sources, making it a highly turbulent region. Hence, in the bulk of the HS the currents will in the average cancel. However, in the outermost narrow current layer centred at the last spiral HS $\mathbf{B}$ field line, the heliospheric magnetopause, both the non-neutralized secondary beam and current effects retain and become dominant. Here electron beams and plasma waves are generated such that this region becomes a source of radiation.

3. Electron beam formation

In weakly magnetised plasmas of large plasma to gyrofrequency ratio $f_{\rm pe}/f_{ce} > 1$ radiation cannot be produced by the cyclotron maser mechanism (Melrose 1980). The most efficient complementary plasma process is radiation mediated by electron beams as known from type III and shock emission processes. HP emission thus reduces to the question of how electron beams can form in the HP environment. Over scales r_{ci} the newly injected HS ion beams behave unmagnetised. Such beams are unstable with respect to the (cf., e.g., Gary 1993, p. 74) LHI, a high-frequency continuous-spectrum whistler wave. The LHI is strong in the sense that its growth rate $\gamma_{{\rm l}h}$ is of the order of the wave frequency

$$\gamma_{{\rm l}h} \sim 2\pi f_{{\rm l}h} \approx 2\pi f_{{\rm p}i}[1 + f_{\rm pe}^2/f_{\rm ce}^2]^{-1/2} \qquad (1)$$

The numerical value of $\gamma_{{\rm l}h}$ depends on $|\mathbf{B}|$. For dense plasmas $(f_{\rm pe} \gg f_{\rm ce})$ one has $f_{{\rm l}h} \approx f_{ce}(m_{\rm e}/m_{\rm i})^{1/2} \approx 0.2 - 1.0$ Hz in the HS. The e-folding times are less than 1 s, and the instability quickly reaches a large amplitude nonlinear state. The LHI is largely independent of parameter changes and grows as well for $T_{\rm i}/T_{\rm e} \gg 1$. It stabilises for $\beta = nk_{\rm B}T/(B^2/2\mu_0) > 1$.

Fig. 2 shows the evolution of the partial pressures and βs in the HSP. There is an extended region in the outer HSP where $\beta < 1$ and thus the LHI should grow. Close to the HP $\beta_{{\rm p}u}$ takes over and increases to become close to $\beta_{{\rm p}u} \approx 1$ if no compression of $\mathbf{B}$ is included. Hence, the LHI would stabilise in the region of interest. However, as discussed above, in the HS, $P_{\rm B}$ is increased by an order of magnitude, sufficient to keep $\beta < 1$. We therefore expect that the LHI grows close to the HP and probably in the HP as well, particularly because here $N_{\rm b}$ and $N_{\rm p}$ both increase steepest. The LHI quickly becomes nonlinear.

Maximum growth $\gamma_{{\rm l}h} \sim 2\pi f_{{\rm l}h}$ is obtained for transverse LH wavelengths $\lambda_{\rm m} \approx 2\pi r_{{\rm c}i}(m_{\rm e}/m_{\rm i})^{1/2}$. Thus $\lambda_{\rm m}$ is a few 100 km. This is the transverse scale of the nonlinear wave packets. Their parallel extension is typically longer by the ratio $(m_{\rm i}/m_{\rm e})^{1/2}$. The most pronounced nonlinear effects are transverse ion acceleration (Karney 1978) and field-aligned electron acceleration (Dubouloz et al. 1995). The latter forms the wanted electron beams. The acceleration is due to resonant stochastic interaction of electrons in the trapped LH wave field inside a nonlinear LH wave packet. It is limited in energy by the finite transition time of an electron along the packet. Electrons accelerated by one packet may either be retarded or further accelerated by other packets. Knowing the nonlinear process of wave packet (caviton) formation it is in principle possible to describe well-developed turbulence of LH wave packets and to derive a distribution function of the cavitons (Dubouloz et al. 1993). Due to additional momentum transfer the beams will in the average gain energy. The beams are small-transverse scale beams flowing in *both directions parallel and anti-parallel* to $\mathbf{B}$. It is these HS-electron beams which are responsible for the excitation of the radiation. The important observation is that the HS close to the HP is filled with such narrow electron beams that emanate from the many nonlinear LH-sources.

4. Radiation

The beam energy is about 16 times the thermal energy of the electrons, accelerated within about 15 LH oscillation times

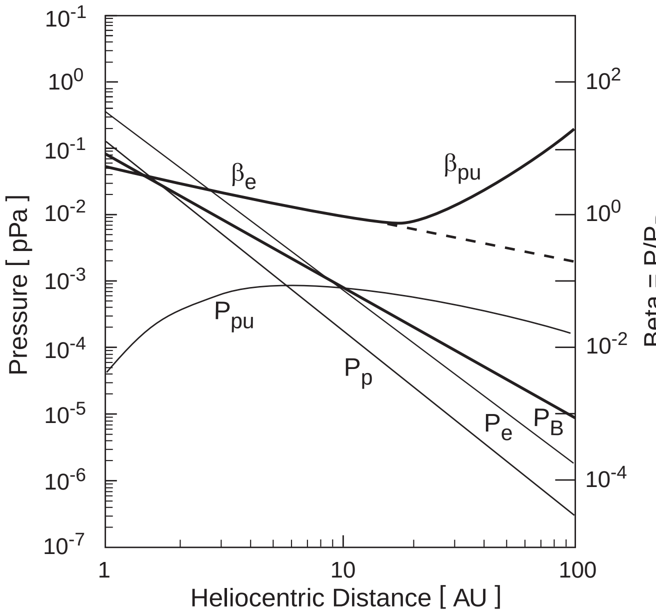

Fig. 2. Different partial pressures Ps and βs in the HSP as functions of heliocentric distance (indices e, p, pu, B signify electron, proton, pick-up and magnetic quantities; the error bars are measurements of the pick-up ion pressure). The SW ram β_{sw} (not shown) remains about constant across the HSP dominating the SW dynamics, while all other partial pressures and βs evolve. In the outer HSP the contribution of the pick-up interstellar ions to the pressures and β starts dominating locally.

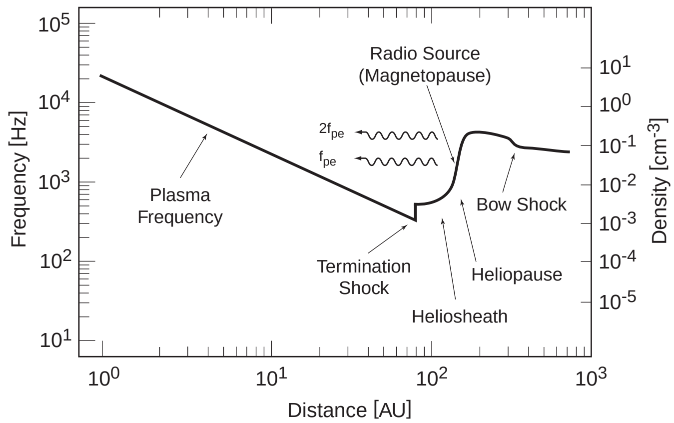

Fig. 3. The scenario of HP emission. Fundamental and harmonic emission is generated in the HP ramp in presence of LH wave turbulence and electron beams at the last Parker spiral $\mathbf{B}$ field line (HSP magnetopause) at ~ 160 AU. Under disturbed conditions the density may increase due to compression. Slow outward motion may cause the observed frequency increase.

(Dubouloz et al. 1995). In the HS this corresponds to $\sim$ a few 10 eV. Relative to the background the beam speed is $v_{\rm b} \approx 4v_{\rm e}$. It satifies the propagation condition for beam excited Langmuir waves, $v_{\rm b} > \sqrt{3}v_{\rm e}$. Langmuir waves excited by beams in the HS, at the foot of the HP, and in the HP ramp region will not be Landau damped because of the low electron temperature of the background plasma and the smallness of the Debye length. Hence, simple linear theory of radiation from beam excited Langmuir waves (cf., e.g., Melrose 1980, Macek 1996) is applicable. The basic process is $\ell + \ell' \to t$, the collision between two oppositely directed Langmuir waves $\ell = (f_{\rm L}, \mathbf{k}_{\rm L})$ and $\ell' = (f_{\rm L'}, -\mathbf{k}_{\rm L'})$. Wave momentum and energy conservation yield [$t = (\mathbf{k}, f)$ is the electromagnetic wave] radiation around twice the plasma frequency

$$\mathbf{k}_{\rm L} - \mathbf{k}_{\rm L'} = \mathbf{k} \approx 0, \qquad f_{\rm L} + f_{\rm L'} = f \approx 2f_{\rm pe} \tag{2}$$

For isotropically distributed Langmuir waves, the conversion efficiency into radiation is

$$\nu \approx 1.2 n\sigma_{\rm T} N_{\rm e} c \langle W_{\rm L}\rangle / m_{\rm e}c^2 \tag{3}$$

where $\langle W_{\rm L}\rangle \gg m_{\rm e}c^2$ is the total average energy of the beam-excited Langmuir waves, and $\sigma_{\rm T}$ is the Thomson scattering cross section. This rate must equal the conversion rate computed from the spectral density of the radio flux F (e.g., Macek 1996)

$$F = \frac{r_{\rm e} n}{5\epsilon_0 m_{\rm e} f_{\rm pe}} \frac{\Delta R}{\Delta f} \frac{\langle W_{\rm L}\rangle^2 k_{\rm L}}{\Delta\Omega_{\rm L}\Delta k_{\rm L}} \int {\rm d}\Omega \frac{v_{\rm b}^3}{c^3} \tag{4}$$

Here $r_{\rm e}$ is the classical electron radius, ΔR the radial extent of the source, $n^2 \approx 3/4$ the index of refraction, Δk the spectral bandwidth, and Ω the solid angle. The spectral distant HSP radio flux density has been measured to be about $F \approx 10^{-17}$ ${\rm Wm^{-2}Hz^{-1}}$ (Kurth et al. 1984) at 2-3 kHz, with bandwidth $\Delta f/f \approx 1/3$. Hence, taking $\Delta\Omega \approx (\pi/8)$ sr, and defining $z \equiv [\Delta\Omega/\Delta\Omega_{\rm L}]/[\Delta k_{\rm L}/k_{\rm L}]$ one obtains for the random mean squared (rms) average Langmuir wave electric field

$$\langle E_{\rm L}\rangle_{rms} \approx 120\mu{\rm Vm}^{-1}(z\Delta R)^{-1/4} \left\langle c/v_{\rm b}\right\rangle^{3/4} \tag{5}$$

The angular brackets indicate averaging over dΩ, ΔR is in AU, $z \gtrsim 2(N_{\rm e}/N_{\rm be})^{0.3}$ (Macek 1996), and $\Delta\Omega \approx \pi/16$. For $v_{\rm b} \approx 1500\,{\rm km\,s^{-1}}$, the rms amplitude producing radiation at $f \approx 2f_{\rm pe}$ is

$$\langle E_{\rm L}\rangle_{rms} \simeq 23\mu{\rm Vm}^{-1}(\Delta R)^{-1/4} \left(N_{\rm be}/N_{\rm e}\right)^{0.075} \tag{6}$$

where we assumed a weak beam to plasma density ratio $N_{\rm be}/N_{\rm e} \approx 10^{-5}$ suggested from SW type III bursts. Actually, the result is nearly independent of the actual value of this ratio. Since the plasma is optically thin (negligible absorption and Landau damping), this field becomes weaker the more radially extended the source region is. However, the decrease is proportional to the fourth root only yielding a drop by a factor of three for the $\Delta R = 100$ AU suggested by Fig. 1. This drop may be balanced by the fact that the many elementary radiation sources are of much smaller size yielding higher local wave amplitudes. We thus find that very modest Langmuir wave intensities in the extended source indeed explain the observed radiation. Trapping of the waves in density variations of ion-acoustic waves, nonlinear collapse (Pottelette et al. 1992) and caviton burnout may contribute to even more intense radiation from low amplitude local sources.

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5. Discussion

The refreshing result of our calculation is that, with relatively weak requirements on the electron beams accelerated in the HS, we are able to reproduce the radiation flux observed by Voyager. The frequency cut-off at 1.8 kHz (Kurth et al. 1984) implies that the radiation source is located at densities $N_{\rm e} \geq 0.04\,{\rm cm}^{-3}$ at ~ 160 AU in the ramp of the ion wall (Fig. 1). Here $N_{\rm b}/N_{\rm p} \approx 5 \times 10^{-5}$ justifying our above assumption on the density of the electron beams. We conclude that the HSP magnetopause (last HSP $\mathbf{B}$ field line) probably is at this position. In fact, however, our estimates are valid under *quiet* conditions. The observed occasional radiation is at higher frequency, sporadic and bursty, while our mechanism is stationary. Gurnett et al. (1993) attribute it to rare violent interaction of fast SW disturbances propagating at high speeds radially outward. Such disturbances will have a 3-fold effect on our mechanism. (a) They transitionally increase the local plasma density in the HS and steepen the density gradient at the HP. (b) They increase $|\mathbf{B}|$, the compression, and thus the LH frequency. (c) The density enhancement by which they are accompanied increases the rate of charge exchange of the interstellar neutrals in the SW. All three effects act in favour of our mechanism. The increase in density lifts the emitted frequency into the range of the Voyager observations and agrees with the observed low frequency band. The increase in $\mathbf{B}$ and steepening of the density gradient increases the LH growth rate and intensifies the generation of electron beams. Both beam density and speed increase. The increase in number density of hot neutrals also increases the number of re-ionised protons in the HS. Altogether, these effects cause an enhanced radiation of electromagnetic waves at frequencies above 1.8 kHz. It is possible to speculate about the drifting structures. Probably, these map the motion of the disturbance up the weak HP-density gradient at $0.004\,{\rm cm}^{-3}$/AU, corresponding to 1.14 kHz/AU at $2f_{\rm pe}$, a drift velocity of 5.3 AU/yr $\approx 25\,{\rm km\,s}^{-1}$. Hence a *slowly* propagating disturbance is required to reproduce the observed 3 kHz/yr drift of the radiation. Such slow drifts suggest that the 'radiation spot' (magnetopause) is slowly moving outward, unlike the *fast* interplanetary disturbance.

A number of alternative mechanisms are possible. One is radio emission from the LIC bow shock (BS). If a BS exists, electron beams will be produced along the LIC-$\mathbf{B}$ emitting radio waves from the LIC foreshock. Observation of this radiation is possible only if it leaks into the HSP through low density 'holes' in the ion wall. The low-frequency cut-off at 1.8 kHz yields too low a LIC density. An attractive possibility to save the model is inclusion of magnetic reconnection. Reconnection may allow electron beams to penetrate into a HSP-boundary layer of cut-off radiation density. Such a mechanism will be explored elsewhere.

It is tempting to speculate about similar radiations from nonmagnetised planetary and cometary atmospheres. Since these are much denser than the interstellar gas one may expect that charge exchange with SW particles will affect the ionisation, generation of LHI, electron beams and radiation. Recent observation of x-rays from comets (Lisse et al. 1996, Dennerl et al. 1997) seem to prove the importance of charge exchange. But radio observations are still very sparse. The artificial comet (Gurnett et al. 1985) with its dilute atmosphere showed some so far unexplained indications of radio wave generation. It will be interesting to investigate if such emission can be traced back to a similar mechanism as the one working at the HP.

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