HELIOSPHERIC RADIO EMISSION THEORY

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Abstract

We review, in a non-mathematical way, the current state of the theory of natural radio emissions in the heliosphere. These emissions can be divided into four categories: solar radio emissions, planetary radio emissions, interplanetary radio emissions, and termination shock radio emissions. The present review excludes solar and proper planetary radiation in plasma and radio waves (for a review of the latter see, e.g., Kurth and Gurnett, [1991]), which by themselves each constitute a wide field, and concentrates on the remaining two phenomena. Radiation in interplanetary space is mainly caused by electron streams either escaping from the solar corona, reflected from planetary bow shocks or originating in traveling interplanetary shock waves and solar wind holes. The main radiation mechanisms are wave-wave interactions in the high-frequency Langmuir mode in both the weakly and strongly turbulent regimes. The contribution of ions is twofold: first in generating sufficient inhomogeneity for electron scattering and in providing low frequency density modulations which may mediate the emission process. Similar menchanisms hold for the termination shock emissions, but here critical ionization of the interstellar medium becomes important. Generally, the importance of ions in radio emissions is not clarified yet. The electron cyclotron maser is probably not working in the interplanetary or interstellar space because of the weak magnetic fields encountered there.

1 Introduction

The zoo of natural radio waves which have their origin in our planetary system encompasses all kinds of radiation from millimeter to tens of kilometer wavelengths. Because of the conditions of propagation of radio waves not all of this radiation can be observed on the Earth. The long wavelength part is reflected from the ionosphere while some of the shorter wavelength radiation is absorbed. The intermediate spectrum from about 20 MHz up to a few GHz is accessible from the ground. However, with some exceptions this frequency range is already too high to be generated in the interplanetary space but originates predominantly in the high density regions of the solar or planetary/cometary atmospheres.

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By far the strongest radiator is the Sun with its quiet and bursty radio emissions. Many types of solar radio bursts are known for a long time (type I through type IV bursts, for a review see McLean and Labrum, [1985]; Melrose, [1987]) and many more kinds of emissions have been discovered during the past two decades (finestructures, spikes, blips and so on; see also, e.g., Benz, [1985]). The sources of most of these bursts are confined to the close vicinity of the solar surface with only type III and type IV bursts invading the interplanetary space (for a recent review see Aschwanden and Treumann, [1997]). The former belong to electron beams which propagate out into space from the Sun along the interplanetary magnetic field lines and are a frequent and common phenomenon. The latter are rare phenomena connected with the ejection of closed magnetic field configurations from the solar surface during flares which trap sufficient amounts of electrons to generate escaping radiation.

It is interesting that just the most violent solar radio emissions connected with traveling shock waves in the solar atmosphere, the type II bursts, have barely been observed farther out in interplanetary space than the extent of the solar corona. This fact is not well understood and throws some light on the generation mechanism of type II burst radiation. There can be no doubt that the type II (blast or piston driven) shock waves reach the interplanetary space. During Coronal Mass Ejections (for a review see, e.g., Webb, [1995]) piston driven shocks have been commonly detected [Cane et al., 1987]. Moreover, many spacecrafts have provided indication of interplanetary shock waves. But there is a lack in some of the shock generated radio emissions inasfar as the emission detected in these shocks is different in its properties from metric and decametric solar type II radiation. The main signature of the latter is the so-called backbone radiation which is missing from piston driven interplanetary CME shock waves while flare related blast waves cease to emit [Reames, 1995] when leaving the corona.

Interplanetary (or heliospheric as it has become fashionable to call them today) radio emissions have been known for a long time (for a recent review see Gurnett, [1995]). Excluding the proper planetary and cometary radio emissions which are generated inside the magneto- and ionospheres of these objects, the interplanetary radio emissions split into essentially three groups: interplanetary type III radio bursts, shock emissions, and outer heliospheric emissions. To treat the last separately makes sense insofar as they result from interaction between the solar wind and the interstellar medium at the outskirts of the heliosphere.

2 Shock Emission

Shock emissions in the heliosphere are nevertheless a common phenomenon. There are at least four sources of such emissions: traveling interplanetary shock waves, shock waves connected to coronal mass ejections, shock waves in front of solar wind holes (funnies), planetary (Figure 1) and cometary bow shocks, and the two shocks believed to exist in the interaction region of the solar wind with the interstellar medium, the heliospheric bow shock and the termination shock.

All these shocks are fast though not necessarily strong shock waves. In particular traveling

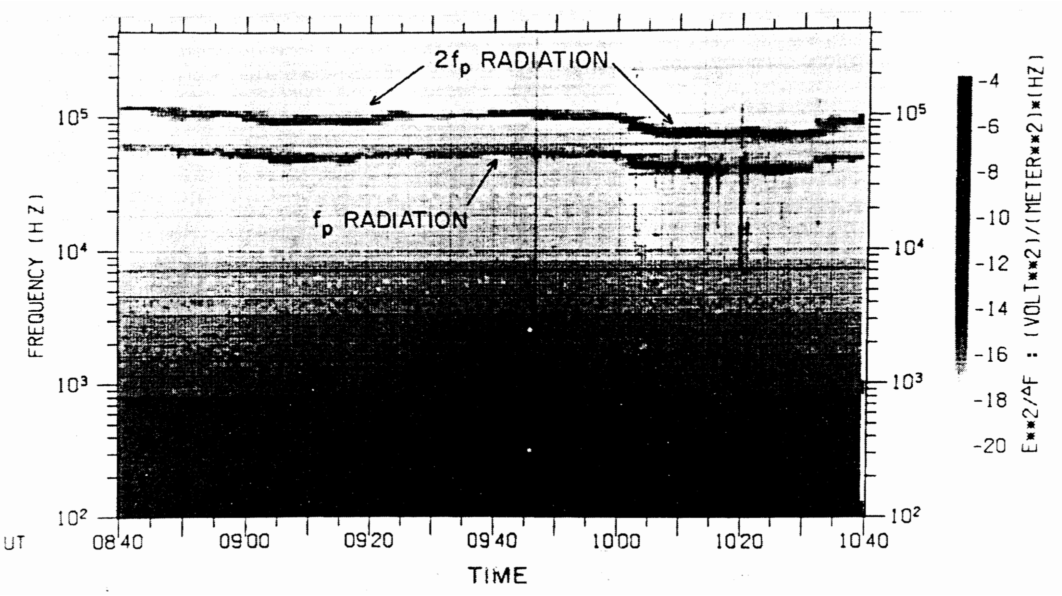

Figure 1: An example of shock emission at the fundamental and harmonic of the local plasma frequency taken with ISEE 1 in front of the Earth's bow shock (from Cairns, [1994]). Part of the signal at the fundamental is local emission of Langmuir waves related to foreshock reflected electron beams.

shocks in the interplanetary medium frequently have low magnetosonic Mach numbers because of the proximity of their velocities to the solar wind speed and thus are weak shocks. Similarly, shocks in front of slow CMEs may be weak shocks while, paradoxically, reverse shocks which travel against the solar wind when resulting from interaction of two interacting corotating regions, are high Mach number shocks und hence in the majority of cases are strong shocks. Because of this simple reason it will not be too surprising that sometimes traveling shocks or even shocks in front of CMEs are not strong radio sources while on the other hand all planetary bow shocks are. The reason is that strong high Mach number shocks readily reflect particles into the direction upstream of the shock and that these particle beams are the main source of the shock radiation. As pointed out above, this seems to be different for coronal shocks the mechanism of radiation of which is hence different from that of interplanetary shocks.

There is basically one mechanism by which interplanetary shocks radiate radio waves. That is, they radiate via the coalescence of Langmuir waves excited by the electrons which are reflected from their fronts (Figure 2). The mechanism of reflection [Sonnerup, 1969; Wu 1984] is to a large part simple specular reflection (the normal velocity component turns by an angle of π which implies that it changes sign) and requires a very thin reflecting shock surface. Since reflection occurs only from strong, supercritical quasi-perpendicular shocks one may conclude that weak subcritical and quasi-parallel shocks will barely radiate. The dense and hot material in the shock front has an increased level of Langmuir fluctuations due to spontaneous emission but there is no known mechanism which could transform these fluctuations into radio waves. Since no high frequency instability arises here the front is radio quiet and hence invisible. (Note however the remarks on electron acoustic waves below!)

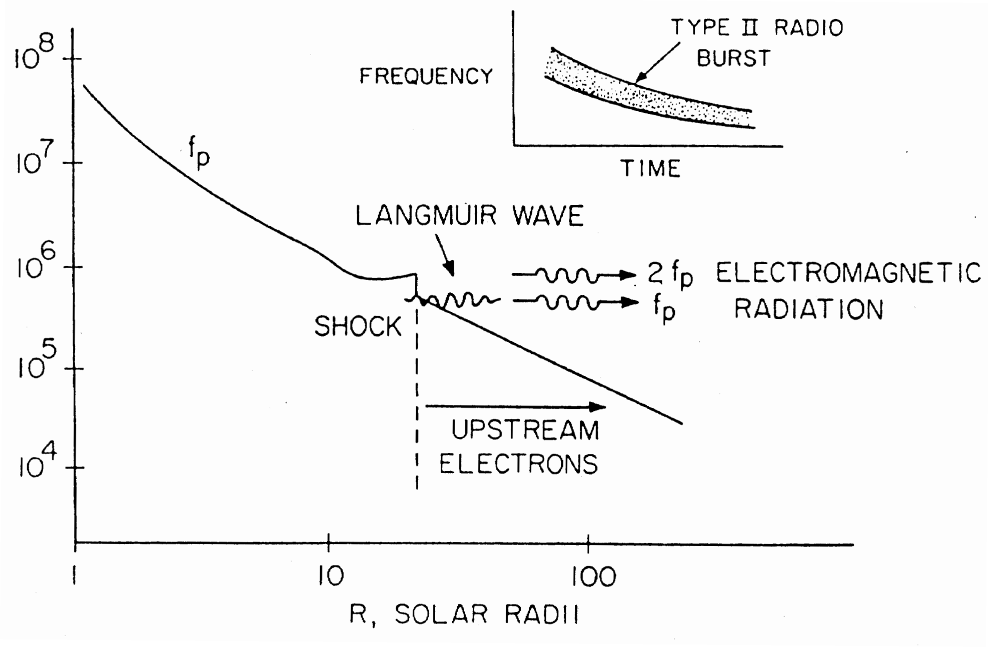

Figure 2: Schematic of shock reflected electron beam causing Langmuir waves and radiation at the fundamental and harmonic (after Gurnett and Kurth, [1996]).

On the other hand the radiation measure of the front in the dilute interplanetary medium is so low that no measurable free-free emission is excited. The radiation is thus entirely due to the electron beams released from the shock into the upstream solar wind from their quasi-perpendicular parts of the shock surfaces. These beams propagate parallel to the tangential magnetic field, excite Langmuir and upper hybrid waves which subsequently are transformed into escaping radiation of frequency above either the plasma or X-mode cut-off. Merely the old naive mechanism is well understood (see, e.g., Melrose, [1985]). It prescribes the head-on collision of two oppositely propagating Langmuir waves such that energy and momentum conservation of the two-plasmon system yields an emission frequency at the second harmonic, $\omega = 2\omega_{pe}$, of the plasma frequency and long wavelength $k \approx 0$ in the X-mode.

A similar mechanism acts for the coalescence of a Langmuir and an ion sound wave if the latter can be unstably excited. In this case the emission is at the fundamental $\omega = \omega_{pe} + k_s c_s$, with $k_s \approx k_\ell$, causing either escaping radiation in the O-mode, or for $k_s c_s$ large enough that the radiated frequency is above the X-mode cut-off, in the X-mode (here c_s is the ion sound speed, and k_s, k_ℓ are the respective wave numbers of sound and Langmuir waves). This all requires weak magnetic fields (or plasma $\beta \gg 1$) as is usually the case in the solar wind. While excitation of Langmuir waves by electron beams is a common process, generation of upper hybrid and ion sound waves requires more special conditions as anisotropies in the electron beam distribution function, electron heat fluxes, non-compensated electric currents or scattering of plasmons on thermal ions, mechanisms of low efficiency in the solar wind and even in front of the shocks.

One exceptional region exists in front of a quasi-perpendicular shock: its foot region [Sckopke et al., 1983; Thomsen et al., 1983; 1985]. Here the reflected and gyrating ions carry a diamagnetic current strong enough to modify the magnetic profile of the shock. Under certain conditions this current can become unstable with respect to the ion-acoustic instability. Actually, the conditions for this instability are very weak. It may not be required for the current drift to exceed the ion sound velocity, $v_D > c_s$ as usually assumed. Ion phase space hole formation [Berman et al., 1985] undermines this condition and generates sound waves long before it is met. One thus expects that ion sound waves populate the foot region. Electron beams reflected from the shock and passing through the foot excite Langmuir waves. Interaction of these with the ion hole sound will result in fundamental emission. This process may constitute the basic unknown backbone emission of shock waves observed in type II bursts. In interplanetary shocks and even planetary bow shocks it is barely observed. This may be either due to strong reabsorption of the fundamental emission or to the inefficiency of both ion hole formation and the coalescence mechanism.

Ordinary interplanetary shock radiation is hence due to electron beam reflection from the shock front along the tangential magnetic field line where it also has been observed [Treumann et al., 1986; Lacombe et al., 1985]. It compares to coronal herring bone emission known from solar and interplanetary type II bursts. Closer resolution of this kind of radiation has sometimes revealed that it appears even in higher harmonics [Treumann et al., 1986; Cairns, 1986; correction in Cairns, 1987; Cairns, 1994] than the second and that each of the harmonics is sometimes resolved into clumps regularly spaced by a small amount corresponding to the electron gyro-frequency. Moreover, observed radiation powers are higher than expected from the naive theory. This all implies that the radiation mechanism might be much more involved. Obviously cyclotron harmonics are involved which points on electrostatic modes which propagate not entirely parallel but are strongly inclined to the magnetic field. In addition secondary Langmuir waves are produced by wave decay processes [Cairns, 1986] giving rise to higher harmonics in the radiation. But the high intensities remain unexplained and have stimulated a wealth of research in the non-linear evolution of Langmuir waves (see, e.g., Goldman, [1983; 1984]). Langmuir collapse has been invoked to trap and keep the plasmons localized, help the electron beams to remain stable over the observed long distances, generate oppositely directed k vectors thereby making easier the local merging of waves and increasing the radiation power by orders of magnitude [Hafizi et al., 1982]. All these theories have been supported by numerical simulations [Newman et al., 1989], but nonetheless agreement with observation is still lacking. The observed modulation of Langmuir waves in front of planetary bow shocks [Gurnett et al., 1993a] is only weak or no [Cairns and Robinson, 1995] support of the theory. Probably collapse evolves if at all so differently. Langmuir waves may be trapped in density cavities caused in different ways by current instabilities or even by ion beam modes which modulate the background. Such ion beams are present in multitude in front of strong supercritical shocks [Sckopke et al., 1983]. The density cavities then have nothing to do with collapse but the trapped waves behave similarly, cause smaller cavities which burn out [Russell et al., 1988] by giving up their trapped wave energy to acceleration of electrons into non-thermal tails. Statistically distributed cavities may constitute the source of preshock radiation. If this is the case, ions play an important and still barely explored role in the radiation mechanism.

The absence of observations of shock radiation from the shock ramp itself is a surprising fact. The ramp contains intense ion sound waves and heated electrons [Feldman, 1985]. But obviously the absence of sufficiently strong electron beams in and behind the front inhibits the generation of radiation. There is only one narrow region in the transition from the foot to the ramp where the cold incoming electron flow mixes into the already hot ramp electron fluid. Here electron acoustic waves can be excited by the electron acoustic instability [Tokar and Gary, 1984; Lin et al., 1985]. These waves have frequencies well below the local electron plasma frequency and grow under very peculiar conditions otherwise resembling Langmuir waves. Their phase speed is below the hot electron thermal but higher than the cold electron thermal speed. Hence for any reasonable solar wind speed they can escape over a certain distance upstream into the solar wind in front of the shock until becoming damped. They also can evolve into solitons modulating the density and thus supporting Langmuir wave trapping. There are several possibilities when these waves may become important for generation of radiation. First, they contribute to harmonic radiation from trapped Langmuir waves. Second, when interacting with Langmuir waves they may generate a broad band of emission between the fundamental and the second harmonic either in the O-mode or X-mode. Third, two electron acoustic waves with frequencies just above the half local plasma frequency when mutually interacting can generate fundamental emission. Finally, because the electron acoustic waves come from the dense ramp of the shock their frequency may be close to the upstream plasma frequency. In the upstream region where they escape radiation produced by them can be at higher and not at regular harmonics of the plasma frequency. Interestingly the electron acoustic waves will not survive transport downstream across the shock ramp because of heavy damping in the hot turbulent plasma. Radiation from this region would be a real surprise and has to our knowledge not yet been reported.

3 Interplanetary Type III Bursts

Interplanetary type III bursts are caused by intense streams of solar electrons escaping from the corona. There is a multitude of observations of these streams (for the most recent reference see Lin, [1997], and Aschwanden and Treumann, [1997]) and of their radiation [Gurnett et al., 1978; Reiner et al., 1995; Hoang et al., 1995]. Both types of radiation, fundamental and harmonic, have been reported frequently. The most interesting observation of the relation between the radiation and the electron fluxes is that large groups of many coronal metric type III bursts combine to form one single interplanetary type III burst [Poquérusse et al., 1997] with the fluxes and the radiation being modulated temporarily according to the velocity spread of these propagating beams and the possible generation of magnetohydrodynamic waves (Figure 3).

The radiation mechanisms of interplanetary type III bursts are exactly the same as those discussed above in the context of the shock reflected electron beams with even greater uncertainty about the stabilization mechanism of the type III electron beams which travel over distances of several astronomical units in the solar wind without any remarkable deceleration or destruction. Radiation intensities are high in the X-mode and sometimes in the O-mode as well. The characteristic lowering of the emission frequency with distance from the sun follows very closely the solar wind density profile and has been used to check

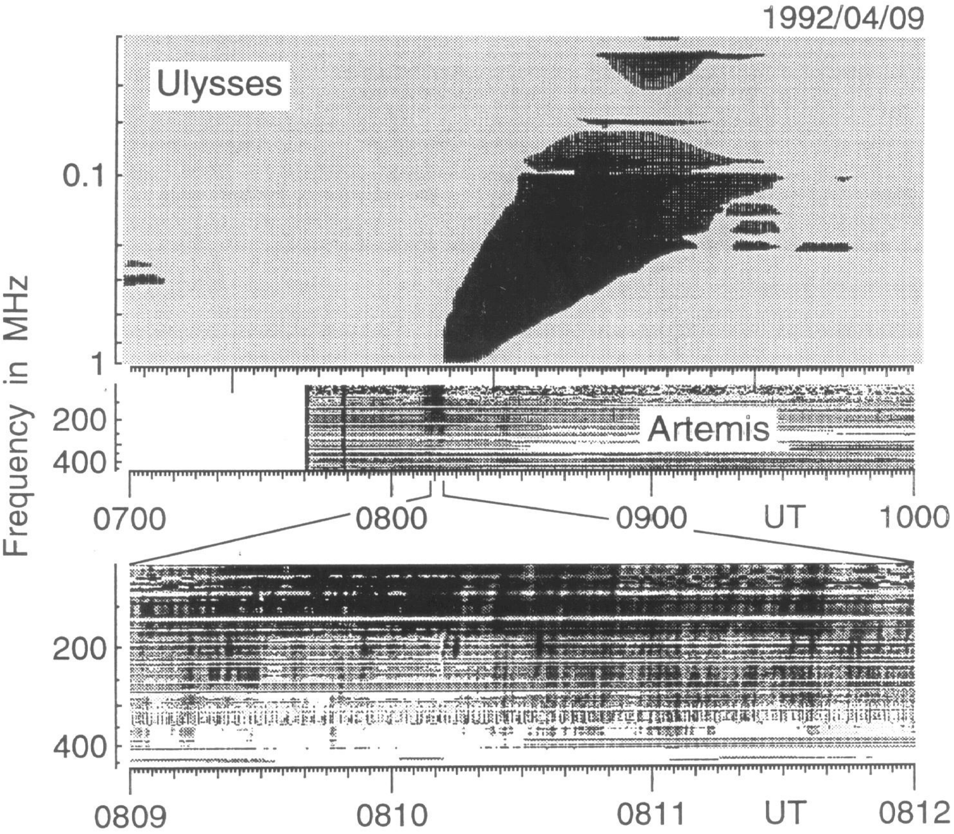

Figure 3: Backtracing of an interplanetary type III burst observed by Ulysses to a group of metric type IIIs in the solar corona measured by Artemis in Nancay, France (from Poquérusse et al., [1997]).

its radial dependence. This has been found to very closely follow the $n \propto r^{-2}$ dependence [Treumann and LaBelle, 1997; LaBelle und Treumann, 1997] known from the expanding solar wind theory (Figure 4). Moreover, intensity of the interplanetary type III bursts is sometimes high enough to cause ionospheric radiation effects like stimulated auroral kilometric radiation. Hence, in such cases planetary radio emission may be the result of stimulation by interplanetary emission [Rosenberg et al., 1995; Calvert, 1995].

Another interesting observation has recently been reported from Ulysses detections of the radial propagation of interplanetary type III bursts. These observations suggest that interplanetary type III radiation is cut-off at about a frequency of 9 kHz [Leblanc et al., 1995]. Type III bursts of lower frequency seem not to exist in the solar wind.

This observation is very interesting because it seems to have only two explanations. Either the radiation mechanism has the property that below 9 kHz it does not work anymore. Or the solar wind type III bursts cease to propagate farther out than up to a distance of 9 kHz. Neither of these explanations is satisfactory. The solar wind density clearly decreases further when propagating farther out in radial distance from the Sun as has been proven by spacecraft observations. It would also be hard to understand why the type III radiation should suffer from propagation effects.

The way out of this dilemma is to take into account collisional damping in the solar

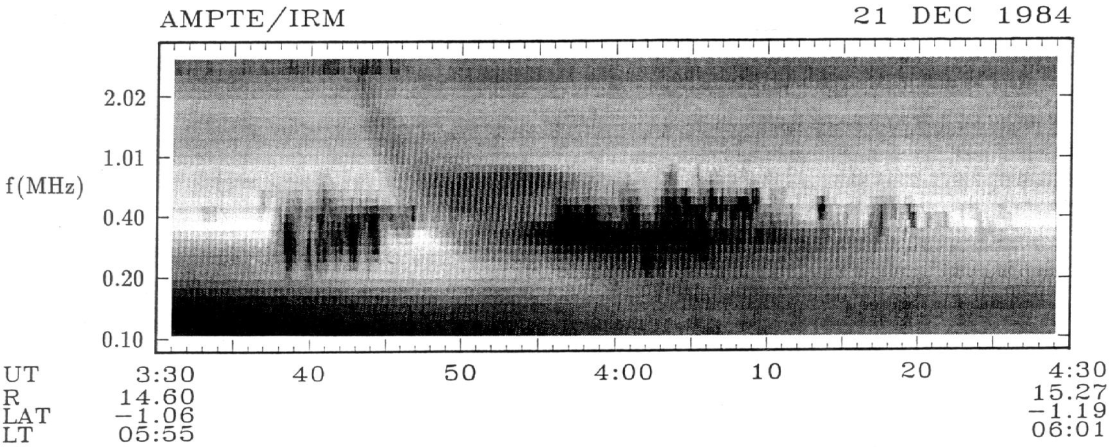

Figure 4: An interplanetary type III burst observed by AMPTE IRM. The typical decay of the frequency with time indicates emission at increasing distance from the Sun.

wind. It is known that Langmuir waves are damped by collisions. Moreover the electron beam will be scattered when collisions come into play and will cease to propagate. In the solar wind the Coulomb collision frequency is small enough to let electrons propagate without any collisions over distances considerably longer than 1 AU. Their scattering is attributed to anomalous processes (non-linear wave and wave-particle interaction) while at the same time this is believed to be inhibited by modulational instability and collapse. For Coulomb collisions no such mechanism of avoidance exists. Hence one can assume that the lower cut-off frequency of observed type III radiation indicates the distance up to that the electron beam propagates. Assuming fundamental radiation and $n(r) \propto r^{-2}$ the cut-off frequency of 9 kHz gives a scattering distance of $r_{sc} \approx \sqrt{40}\mathrm{AU} = 6.2\mathrm{AU}$ for the type III beam. Here we assumed that at $r = 1$ AU the solar wind density is 10 cm^{-3}. Outside this distance type III electron beams will cease to exist. The value obtained is fairly reasonable when taking into account the dependence of the Coulomb collision frequency on density and temperature. One thus concludes that no mystery is hidden behind the low frequency cut-off and no intrinsic modification of the type III emission mechanism must be called for.

4 Outer Heliospheric Emissions

Interplanetary type III bursts will therefore be generated not much farther out than the orbit of Jupiter. The outer heliosphere thus turns out to be a dilute and cool radio-quiet region. The radio sources therein are interplanetary shock waves which are stable enough to propagate over distances that long, the bow shocks of the large magnetized planets and possibly some local sources in the interplanetary current layer giving rise to weak emissions.

However, in contrast to this belief a weak radio emission has been detected in the outer heliosphere by the Voyager spacecraft with frequency between 2-3 kHz. A survey of its observation and explanation has been given by Gurnett and Kurth [1996]. It has been

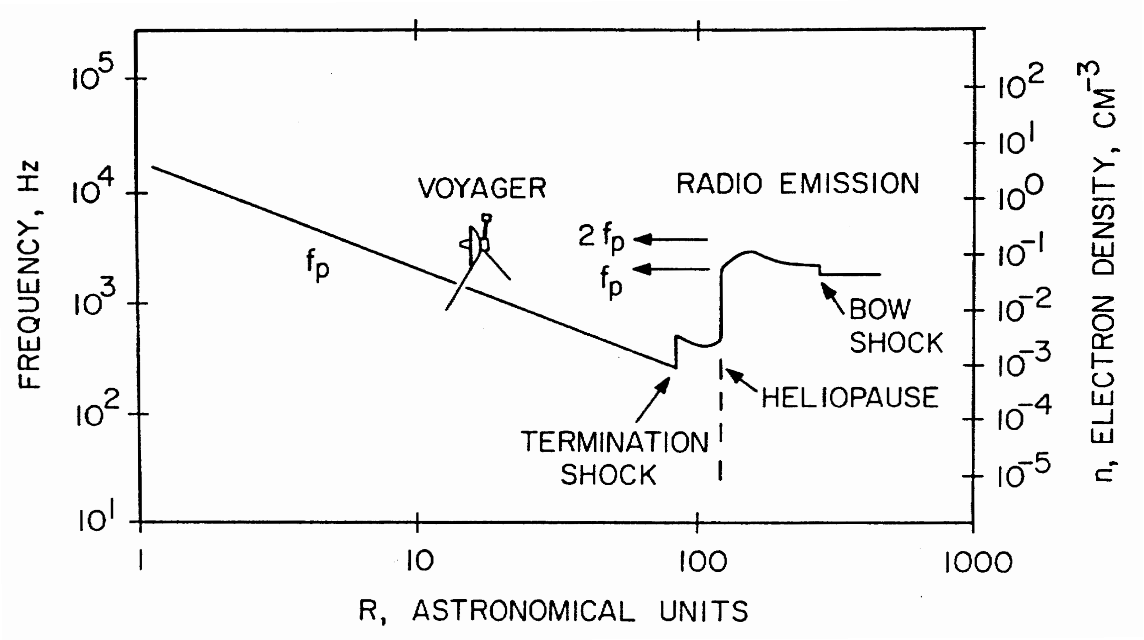

Figure 5: Schematic of the variation of the interplanetary solar wind density with distance to the termination shock-heliopause system and the emission of narrow band radiation. The radiation at Voyager position is detectable only as long as it is above the local plasma frequency (from Gurnett and Kurth, [1996]).

found that it is correlated with intense solar particle events but exhibits a long time delay of the order of several hundred days (400 days in one particular case in 1982), the time corresponding to a fast shock travel time across the heliosphere out to its boundary, the heliopause separating the interstellar medium from the interplanetary plasma. Gurnett and Kurth [1996] therefore proposed that the enhancements of this emission are caused by the interaction of a system of shocks with either the termination shock or the heliopause (Figure 5). The emission mechanism is believed to be one of the above discussed simple shock radiation mechanisms, probably emission at the second harmonic resulting from shock reflected electrons. Gurnett and Kurth [1996] and Macek [1996] argue that the emitter is rather the heliopause with its higher density than the termination shock the radiation from which would have lower frequency and would not reach the much closer to Earth Voyager position because of reflection from the solar wind gradient.

It is interesting to note that of the two Voyager spacecraft Voyager 1 was at a larger distance than Voyager 2 and detected emission extending to lower frequencies than detected by Voyager 2 which is consistent with the view that Voyager 1 was at the lower solar wind density. This observation suggests that the radiation was generated even farther out in the outermost parts of the heliosphere. Hence the assumption that its source can only be in the highly distorted transition region between solar wind and interstellar medium. This region has a complicated physics because it results from interaction of the supersonic though very dilute fully ionized solar wind plasma with the neutral cold interstellar gas.

This kind of interaction is nontrivial because both media are essentially collisionfree. The transition must be of a very specific nature and, because of the extraordinarily large mean free path, must be of enormous extension. At such long distances from the Sun photoionization should become entirely unimportant though it has been used extensively in calculations and simulations. Fluid theories (see, e.g., Baranov and Malama, [1993]; Lallement et al., [1993]; Baranov and Malama, [1996]; Lallement et al., [1996]) are based on charge exchange between neutrals and plasma and hence depend heavily on the assumption of a collision frequency. It may be suggested that the critical velocity ionization effect (see, e.g., Brenning, [1992]) proposed by Alfvén [1960] is responsible for fast mixing. If this is the case, the high ionization in the interaction region will lead to retardation of the solar wind, compression, and pile-up of the freshly ionized interstellar gas which acts as an obstacle and causes the termination shock on the solar wind side (which actually is the bow shock of the interstellar gas) to develop. Between the termination shock and the heliopause one finds an extended region of enhanced density, temperature, magnetic field, and low flow velocity below the magnetosonic speed ($v < c_{ms}$). The heliopause will be a highly dynamic region resembling a planetary magnetopause. The nature of the discontinuity is not well understood. It is usually believed to be a contact discontinuity of arbitrary density jump. But since both the solar wind and interstellar medium carry however weak magnetic fields, it can be expected that reconnection between the solar wind and interstellar magnetic fields is going on at this interface destroying the properties of a contact discontinuity. Behind it a broad region of enhanced ionized and compressed interstellar gas and field, the pile-up region exists which is believed to be truncated farther out by another shock wave, conventionally called the bow shock. This shock must be an ionization shock.

All these regions may contribute to radio emissions. Extrapolating the solar wind density out to the termination shock one finds that the plasma frequency at this place is ~200 Hz. Hence, no radio emission neither at the fundamental nor at the second harmonic emitted by reflected electron beams from the termination shock could be detected at the two positions of the Voyager spacecraft. The termination shock is practically invisible. It has thus been dismissed by Gurnett and Kurth [1996] and Macek [1996] as the source of the observed radiation. Moreover, our experience with bow shocks and interplanetary shocks tells us that the turbulent region behind the shock and the shock front itself barely generate radio emissions. Compression of the plasma by a factor of at most 4, taken from shocked fluid theory (see e.g., Tidman and Krall, [1971]), yields second harmonic emission at 1.6 kHz, closer to the observed frequency. But the mechanism required is based on electron acoustic wave generation as cause of the backbone of the termination shock as discussed in the shock section above. The heliopause as the surface of pressure equilibrium between the two media is therefore assumed as the emitter source. Simple pressure equilibrium yields plasma densities < 0.1 cm^{-3} from fluid theory developed by Lallement et al. [1993]. The corresponding plasma frequencies cover the range of the Voyager observations.

It is, however, not clear how such a surface should radiate. Experience from the magnetopause and cometary boundaries does not give any hint on radiation. The Earth's and Jupiter's magnetopauses are radio-quiet. Hence, in case the heliopause is a radio source it must be due to the particular nature of the heliopause as a boundary between two plasmas of entirely different composition.

One possibility is that the radiation is produced in the critical velocity ionization process itself. In this process intense lower hybrid waves are excited within the contact interface by the freshly ionized pick-up ions. These waves enhance the anomalous collision frequency and cause additional ionization until saturation. At the same time they accelerate electrons by transit time acceleration stochastically as well as during collapse [Shapiro et al., 1995] into long non-thermal tails [Melatos and Robinson, 1996; Dubouloz et al., 1995] along the magnetic field which result into escaping electron beams. This closes the scenario because these beams excite Langmuir waves and set the conditions for either fundamental or harmonic emission. It is not clear whether this process takes place at the heliopause or at the bow shock. But in both cases the detection of outer heliospheric radio emissions is an indicator of the interaction process going on between the interstellar medium and the terminated solar wind.

5 Conclusion

The heliosphere as radio emitter is now well established, and we believe that we roughly understand by now what are the sources of these emissions. Shocks are weak radiators in general in the heliosphere proper in particular when they are traveling at nearly the solar wind speed. The reason is that they simply do not reflect many electrons and therefore do not radiate. Strong CME-piston driven shocks reflect electrons and radiate. The front itself is no radiator, and the region behind the shock though sometimes believed to radiate by radioastronomers has never turned out to justify this belief. Planetary bow shocks are radiators in various frequencies, however. This radiation can be used to infer about acceleration processes, to remotely sound the density in front of the shock. The most interesting shock radiation comes from the termination region of the heliosphere. We have discussed what is known about the mechanisms and what can be learned from observation of the radiation.

We have put forward some arguments for the critical velocity ionization effect to work at the heliopause and to be of importance for the radiation received from this place. It is most interesting that just this radiation gives almost the only tool at hand to infer about the physical state of the boundary region of our solar system where it merges into the surrounding interstellar gas. Finally, type III radiation seems to be confined to the inner region of the solar system within about 6-7 AU. The reason is that at such distances Coulomb collisions become susceptible and the type III electrons are scattered out of their path. Therefore, the outer heliosphere is probably radio-quiet, though one never knows if or not it may come up with more surprises once more sensitive intrumentation is available or spacecraft will pass through it. However, basic plasma physics permits only radiation far above the local outer heliospheric plasma frequency to be accessible near the orbit of the Earth. The importance of the radiation is justified in many ways not least by the fact that the termination radiation has only been discovered by far flying spacecraft carrying instrumentation capable of detecting radiation at radio frequencies. Without those the outer heliosphere would have stayed in the dark.

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