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HELIOSPHERIC RADIO EMISSIONS

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Abstract. A review is given of heliospheric radio emissions. Only radio emissions generated well away from the Sun (beyond a few solar radii) and well away from the magnetized planets are considered. These consist of (1) type III radio bursts, (2) type II radio bursts, and (3) heliospheric 2-3 kHz radio emissions. The physical processes involved in the generation of each of these radio emissions are described with an emphasis on recent developments. A prognosis is given of advances that can be expected from the forthcoming flight of Ulysses over the poles of the Sun and the flights of Voyagers 1 and 2 to the outer limits of the heliosphere.

I. Introduction

The heliosphere is the region around the Sun where the solar wind has a controlling influence. Five spacecraft, Pioneers 10 and 11, Voyagers 1 and 2, and Ulysses are now exploring the heliosphere. These missions are highly complementary. Pioneers 10 and 11, and Voyagers 1 and 2 are providing measurements at increasingly large radial distances from the Sun (58.6, 39.8, 54.5, and 41.9 AU, respectively, as of January 1, 1994), and Ulysses is providing measurements at high latitudes, over the poles of the Sun, at distances on the order of 2 AU. Three of these spacecraft, Voyagers 1 and 2, and Ulysses, carry radio and plasma wave instruments [Scarf and Gurnett, 1977; Stone et al., 1992]. In this paper we review the various types of radio emissions generated in the heliosphere. To restrict the scope of this review, we will only consider radio emissions generated well away from the influence of strong solar magnetic fields (beyond a few solar radii), and well away from the magnetized planets. Only three types of radio emissions fit these conditions. They are: (1) interplanetary type III radio bursts, (2) interplanetary type II radio bursts, and (3) heliospheric 2-3 kHz radio emissions. To carry out this review, it is convenient to start with a discussion of type III radio bursts, which have been studied in the greatest detail, and to end with a discussion of the heliospheric 2-3 kHz radio emissions, which have been discovered most recently.

II. Interplanetary Type III Radio Bursts

Type III radio bursts are produced by energetic electrons from solar flares and are characterized by an emission frequency that decreases rapidly with increasing time. These bursts were first studied by Wild [1950] who showed that they are associated with solar flares. Wild suggested that the radio emission is produced at or near the local electron plasma frequency, ($f_p = 9\sqrt{n_e}$ kHz, where n_e is the electron density in cm^{-3}),

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as the particles ejected by the flare move outward through the solar corona. Lin [1970] was the first to show that the particles involved are electrons. The electron energies are typically in the range from a few keV to several hundred keV. Radio direction-finding measurements [Fainberg et al., 1972] show that the electrons stream outward along the interplanetary magnetic field lines as shown in Figure 1. Since most solar flares occur at relatively low solar latitudes, less than 30° [Hundhausen, 1993], type III radio bursts are basically a low latitude phenomena [Dulk et al., 1986].

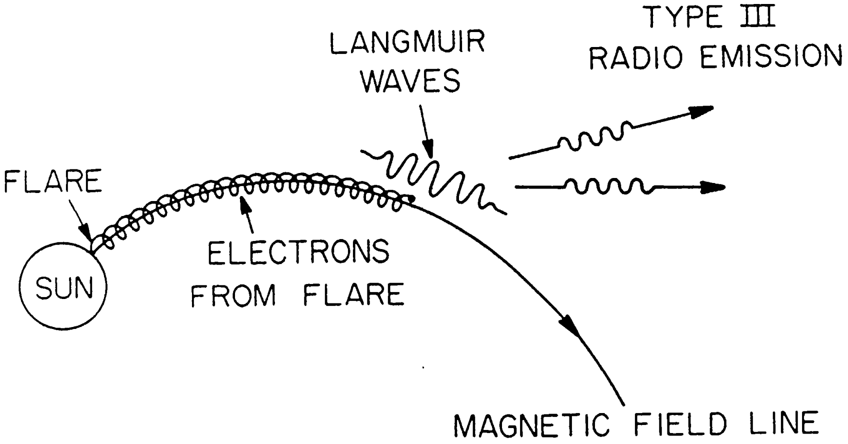

Fig. 1. Type III radio bursts are produced by energetic electrons from solar flares. The electrons stream outward from the Sun along the solar wind magnetic field lines and produce electrostatic oscillations called Langmuir waves. The Langmuir waves then mode convert to electromagnetic radiation via nonlinear wave-wave interactions.

The downward frequency drift of a type III solar radio burst is caused by the decreasing electron plasma frequency encountered by the energetic electrons as they stream outward from the Sun. According to presently accepted ideas, the radio emission is produced by a two-step process in which (1) the energetic electron beam first excites electrostatic oscillations called Langmuir waves at the plasma frequency, f_p, and (2) the Langmuir waves are then converted to electromagnetic radiation via non-linear wave-wave interactions (see Figure 2). This mechanism was first proposed by Ginzburg and Zheleznyakov [1958], and later confirmed by direct in situ observations with the Helios spacecraft [Gurnett and Anderson, 1976]. It is well known that Langmuir waves are generated whenever a beam of sufficient intensity streams through an otherwise quiescent plasma (see Krall and Trivelpiece [1973]). From very general considerations, it can be shown that the Langmuir wave growth rate is proportional to $\partial f/\partial v$, where f is the electron distribution function. An example of a type III burst showing the arrival of electrons from the solar flare, the positive slope in the distribution function ($\partial f/\partial v > 0$), and the simultaneous generation of Langmuir waves is shown by Lin et al. [1986].

Dynamic spectrum measurements [Wild et al., 1954a] show that type III radio emissions are sometimes observed at both the fundamental (f_p) and the harmonic ($2f_p$).

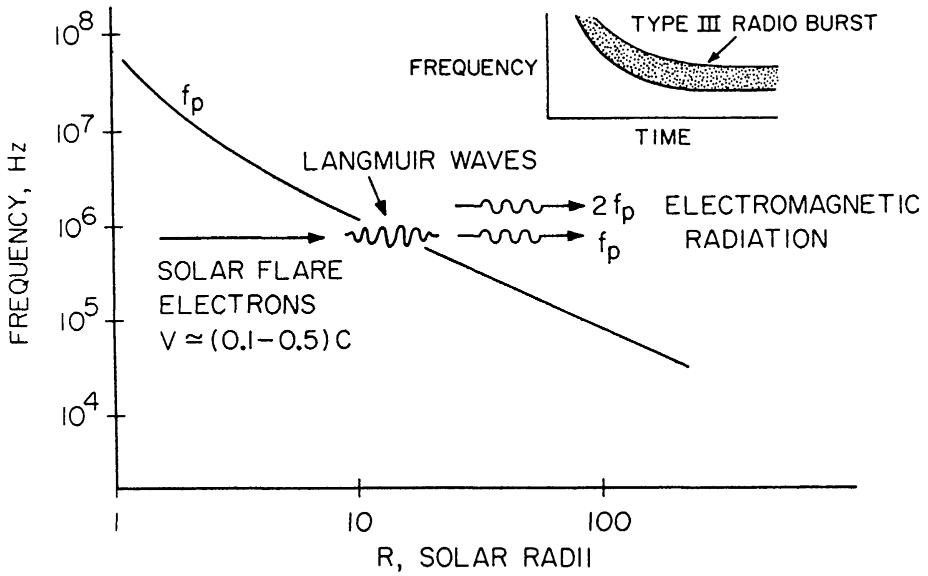

Fig. 2. The downward frequency drift of a type III radio burst is caused by the decreasing electron plasma frequency, f_p, encountered by the solar flare electrons as they stream outward from the Sun. Electromagnetic radiation is produced at f_p and $2f_p$ by mode conversion from Langmuir waves.

According to current ideas the fundamental emission is believed to be produced by a wave-wave interaction between the beam-generated Langmuir wave (L) and a low-frequency ion-sound wave (S). This interaction is often represented by the process L + S → T, where T is the transverse electromagnetic wave. From very general principles (conservation of energy and momentum) it can be shown that the frequencies and wave vectors of the interacting waves must obey the relations $\omega_L+\omega_S=\omega_T$, and $\vec{k}_L + \vec{k}_S = \vec{k}_T$. Since $\omega_S \ll \omega_L \simeq \omega_p$, the energy conservation condition shows that the frequency of the emitted electromagnetic wave must be slightly above the electron plasma frequency. Since the wave number of the Langmuir wave is much larger than the wave number of the electromagnetic wave, $k_L \gg k_T$, the momentum conservation condition shows that $k_S \simeq - k_L$. This relationship shows that the ion-sound wave has a wavelength comparable to the Langmuir wave, and is propagating in the opposite direction. The emission at the harmonic is believed to be produced by a wave-wave interaction between the beam-driven Langmuir wave (L) and a second Langmuir wave (L′) such that L + L′ → T. The frequencies and wave vectors of the interacting waves must satisfy the relations $\omega_L + \omega_L{}' = \omega_T$, and $\vec{k}_L + \vec{k}_L{}' = \vec{k}_T$. Since $\omega_L \simeq \omega_L{}' \simeq \omega_p$, the energy conservation condition shows that $\omega_T \simeq 2\omega_p$. Since again $k_L \gg k_T$, the momentum conservation condition shows that $k_L{}' \simeq -k_L$. This relationship shows that the second Langmuir wave has a wavelength comparable to the beam-driven Langmuir wave, and is propagating in the opposite direction.

Considerable theoretical attention has been given to the origin of the oppositely propagating waves (S and L′). These waves are thought to arise spontaneously from the beam-driven Langmuir wave via nonlinear decay processes. Although the general principles involved are known, the detailed mechanisms involved are poorly understood and still subject to experimental verification. At least two types of low-frequency waves (one electrostatic, and the other electromagnetic) have been observed in association with beam-driven Langmuir waves [Lin et al., 1986; Kellogg et al., 1992]. Since harmonic emission is usually dominant at the radial distance where direct in situ satellite observations are available [Kaiser, 1975], it is not clear which, if any, of these waves plays the role of S in the fundamental emission process. Recently high-time resolution electric field waveform measurements from the Galileo spacecraft have shown that Langmuir waves associated with a type III radio burst have a characteristic beat pattern [Gurnett et al., 1993a]. This beat pattern is produced by two closely spaced narrowband components. One of these components is believed to be the beam-driven Langmuir wave (L), and the other is believed to be the oppositely propagating Langmuir wave (L′) involved in the harmonic emission process. Cairns and Robinson [1992] have suggested that the oppositely propagating wave is produced by a nonlinear parametric instability.

If the Langmuir wave electric field becomes sufficiently intense a highly nonlinear process called soliton collapse can occur [Zakharov, 1972]. In this process the electric field pressure of the Langmuir wave becomes so large that a depression is produced in the plasma density. The density depression then acts to focus the Langmuir waves into the depression, further increasing the electric field pressure. This feedback process ultimately leads to the collapse of the wave field into small, extremely intense soliton-like packets. Because of the intense fields generated in the collapsed wave packets, these regions are expected to be strong sources of electromagnetic radiation. The change in the wavelength as the collapse proceeds also has the effect of shifting the waves out of resonance with the beam. This shift away from resonance ($\omega/k = V_b$) is believed to answer a long-standing question, which is why the beam is able to propagate such long distances without being disrupted by the resonant Langmuir waves. For a discussion of these and other effects see Papadopoulos and Freund [1978].

Because of the importance of the soliton collapse process, there has been considerable interest in determining whether the Langmuir waves observed in association with type III radio bursts have the expected soliton-like structure. For many years it has been known that the Langmuir waves associated with type III bursts are very spiky, with intense bursts occurring on time scales of a fraction of a second or less [Gurnett and Anderson, 1976]. However, until recently, the available measurements did not have sufficient temporal resolution to resolve the extremely small spatial scales (~ten Debye lengths) at which Langmuir solitons are expected to occur. The first clear observation of Langmuir wave solitons was recently reported by Kellogg et al. [1992], using a Fast Envelope Sampler on the Ulysses spacecraft. These data show the existence of very intense spikes on time scales of about one millisecond, with peak amplitudes of a few mV/m. These spikes are usually imbedded in a background of Langmuir wave emissions with intensities of a few hundred μV/m. At a nominal solar wind velocity of 400 km/s the duration of the spikes corresponds to spatial scales of roughly ten Debye lengths, which is the expected size of Langmuir solitons.

III. Interplanetary Type II Solar Radio Bursts

Interplanetary type II radio bursts are produced by shock waves propagating outward through the solar corona and are characterized by an emission frequency that decreases slowly with increasing time. These radio bursts were first studied in detail by Wild et al. [1954b] who suggested that they were produced by shock waves. It is now known that the shock waves responsible for type II radio bursts are produced by coronal mass ejections (CMEs), which are transient ejections of material from the Sun [Hundhausen, 1993]. CMEs are often, but not always, associated with solar flares and other forms of solar activity. Since CMEs can occur at any solar latitude, the distribution of type II radio bursts is expected to be essentially independent of latitude. For a discussion of the relationship between these various phenomena, see Gosling [1993].

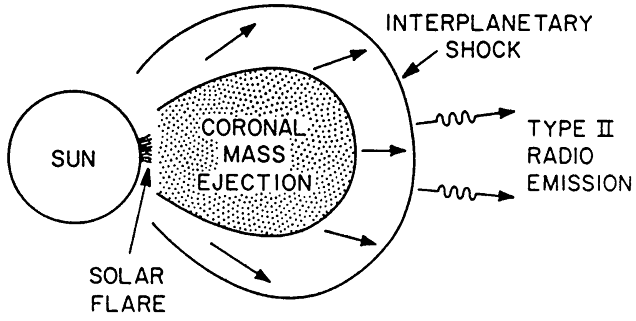

Fig. 3. Type II solar radio bursts are produced by interplanetary shocks driven by coronal mass ejections.

When a shock is produced by a CME, it expands outward as illustrated in Figure 3. As with type III radio bursts, type II radio bursts are believed to be produced by mode conversion from Langmuir waves, very similar to the two-step process involved in the generation of type III radio emissions. However, the electron beam originates from the shock rather than from the Sun. Radiation is observed at both the electron plasma frequency, f_p, and the harmonic $2f_p$. Since the plasma frequency decreases with increasing radial distance from the Sun, the emission frequency decreases with increasing time (see Figure 4), very similar to a type III solar radio burst. However, since the shock propagation speed is much less than the speed of the electrons responsible for type III radio bursts, the frequency drift rates of type II bursts are much slower. Typical shock propagation speeds in the solar wind are in the range from five hundred to one thousand km/s.

Unfortunately, because the source of the type II radio emission seldom extends out to the orbit of the Earth, where in situ spacecraft measurements are available, it has not been possible to verify the details of the type II radio emission process to the same extent that has been possible for type III radio bursts. From various interplanetary spacecraft it is known that Langmuir waves often occur ahead of interplanetary shocks [Gurnett et al., 1979; Kennel et al., 1982]. These Langmuir waves are believed to be produced by electrons accelerated at the shock, very similar to the electron acceleration and generation of Langmuir waves at the planetary bow shocks [Scarf et al., 1971; Filbert and Kellogg, 1979]. At the Earth's bow shock, Langmuir waves are known to produce electromagnetic radiation at f_p and $2f_p$ via nonlinear wave-wave interactions

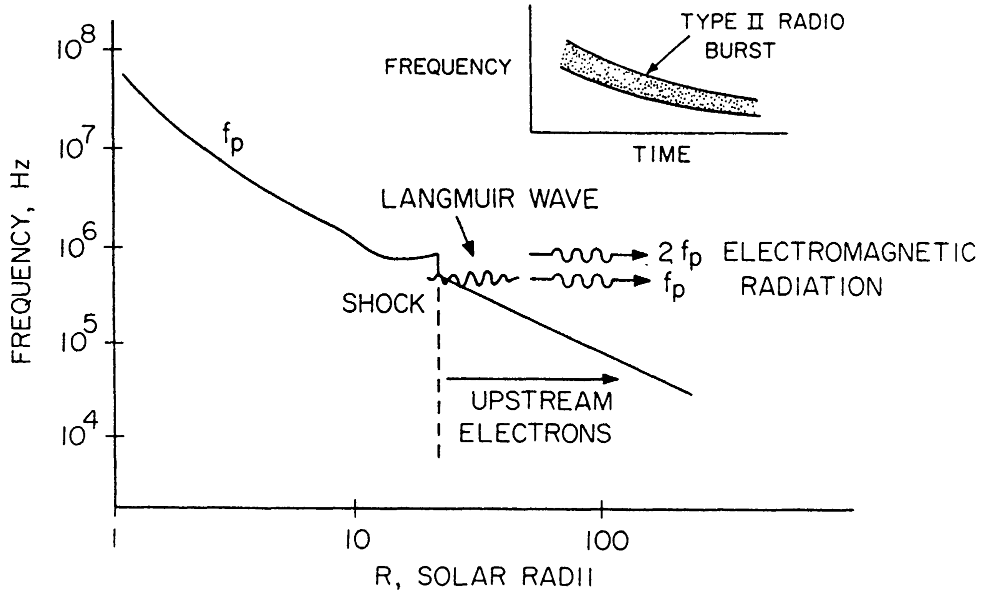

Fig. 4. The downward frequency drift of a type III radio burst is caused by the decreasing electron plasma frequency encountered by the interplanetary shock as it propagates outward from the Sun. Electrons accelerated at the shock are believed to produce Langmuir waves which mode convert to electromagnetic radiation at f_p and $2f_p$.

similar to those believed to occur in type II radio bursts [Dunckel, 1974; Gurnett and Frank, 1975; Hoang et al., 1981].

Langmuir waves are not always observed ahead of interplanetary shocks [Kennel et al., 1982]. The controlling factor is believed to be the orientation of the solar wind magnetic field. From studies of the Earth's bow shock, it is known that the electron acceleration at the shock is most intense and energetic for quasi-perpendicular shocks, where the magnetic field is nearly perpendicular to the shock normal [Anderson et al., 1979]. This magnetic control may explain why the type II radio emission is not generated uniformly over the surface of the shock front, but instead originates from small isolated regions [Nelson and Robinson, 1975].

Although radiation from an electron beam streaming out ahead of an interplanetary shock provides an appealing picture of the generation of type II radio emissions, it is by no means clear that this picture provides a complete description of the type II radio emission process. Comparisons of radio direction-finding observations with spacecraft coronagraph images of coronal mass ejection events [Wagner, 1983] and other techniques [Lengyel-Frey, 1992] show that the radio emission source is often located behind the shock front. Such observations suggest that other processes may be operative to excite Langmuir waves and radio emission in the turbulent region behind the shock front. For a further discussion of type II radio emission mechanisms, see Nelson and Melrose [1985].

IV. Heliospheric 2-3 kHz Radio Emissions

For over ten years the Voyager 1 and 2 spacecraft have been detecting an unusual radio emission in the outer heliosphere in the frequency range from about 2 to 3 kHz. Two particularly strong events have occurred, the first in 1983-84 [Kurth et al., 1984] and the second in 1992-93 [Gurnett et al., 1993b]. Five other much weaker events have also been observed, one in late 1985, one in 1989, and three in 1990-91 [Kurth et al., 1987; Kurth and Gurnett, 1991]. Several possible sources have been considered, including (1) planetary, (2) heliospheric, and (3) stellar. Since the solar wind electron plasma frequency does not drop below 2 kHz until roughly the orbit of Saturn, the source of these radio emissions must be located relatively far from the Sun, at least $R \gtrsim 10$ AU. The total radiated power has been estimated by Gurnett et al. [1993b] to be at least 10^{13} W, which effectively rules out planetary sources (also see Gurnett and Kurth [1994]). Stellar sources, such as pulsars, are difficult to rigorously rule out, but tend to involve implausibly large radiated powers when the propagation must extend over interstellar distances.

The best current explanation of the 2-3 kHz radio bursts is that the emissions are produced in the outer regions of the heliosphere by a disturbance propagating outward from the Sun. The size of the heliosphere is controlled by pressure balance between the solar wind and the interstellar medium [Parker, 1963]. As currently envisaged, the interface between the solar wind and the interstellar medium consists of a shock, called the terminal shock, where the solar wind flow becomes subsonic, and a contact discontinuity, called the heliopause, where the solar wind pressure is balanced by the pressure of the interstellar medium. Because the Sun is moving through the local interstellar medium at a speed of about 26 km/s [Lallement et al., 1993], the heliopause is expected to form a bullet-shaped boundary around the Sun. The distance from the Sun to the nose of the heliosphere is estimated to be on the order of 100 AU. If the interstellar plasma flow is supersonic, a second shock, called the bow shock, is expected to form in the interstellar plasma flow around the heliosphere. For a further discussion of the structure of these boundaries, including the effect of neutral gas interactions, see the reviews by Axford [1990] and Suess [1990]. No spacecraft has yet reached either the terminal shock or the heliopause.

McNutt [1988] first suggested that a solar wind disturbance could "trigger" a burst of 2-3 kHz radio emission. He proposed that the radio emission was produced by an interaction of a high-speed solar wind stream with the terminal shock. This idea was further explored by Grzedzielski and Lazarus [1993], who identified a series of dynamic pressure increases in the solar wind that they believed were responsible for the 1983-84, 1985, and 1989 events, again assuming an interaction with the terminal shock. Despite the possible merit of this idea, the cause-effect relationship was not convincingly established. Later, in the process of studying the 1992-93 radio emission event, Gurnett et al. [1993b] discovered that the large radio emission events in 1983-84 and 1992-93 both occurred about 400 days after large Forbush decreases in the cosmic ray intensity. This relationship is illustrated in Figure 5, which shows the cosmic ray intensity from the Deep River neutron monitor in the top panel, and the 3.1-kHz radio emission intensity from Voyager 1 in the bottom panel. The two Forbush decreases, marked A and B in Figure 5, were produced by periods of intense solar activity in mid-July, 1982, and late-May/early-June, 1991. These were the two largest Forbush decreases (21% and 30%, respectively) observed in over 30 years for which such data are available. As can be seen, the 1983-84 radio emission event started about 412 days after event A, and the 1992-93 radio emission event started about 419 days after event B. It is well known that Forbush decreases are caused by a global interplanetary shock and associated magnetic disturbances propagating outward from the Sun. In both cases the shocks and associated disturbances were detected by a variety of interplanetary spacecraft. For a discussion of these events, including estimates of the propagation speeds, see Van Allen and Randall [1985], Webber et al. [1986], Van Allen and Fillius [1992], and Webber and Lockwood [1993].

Based on the above observations, a strong case can be made that the 2-3 kHz radio emissions are produced by the interaction of an interplanetary shock with the outer

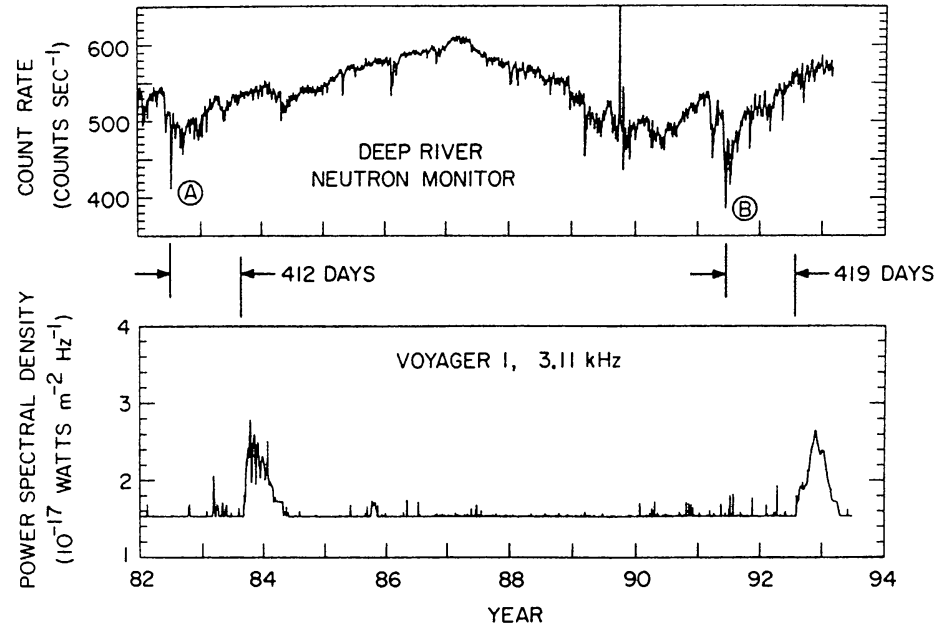

Fig. 5. The top panel shows the cosmic ray intensity from the Deep River neutron monitor over a 12-year period from 1982 to 1994. The bottom panel shows the corresponding 3.1-kHz heliospheric radio emission intensity detected by Voyager 1. The strong radio emission events in 1983-84 and 1992-93 occurred about 400 days after two large Forbush decreases, marked A and B. These Forbush decreases were caused by interplanetary shocks and associated disturbances propagating outward from the Sun after periods of intense solar activity in 1982 and 1991.

boundaries of the heliosphere. Two obvious boundaries could be involved in this interaction, the terminal shock and the heliopause. For the typical shock propagation speeds involved, which are in the range from 550 to 800 km/s, the long transit time, $\sim$400 days, would indicate that the interaction must take place at a distance from the Sun of at least 100 AU. At the present time, there is only one known mechanism that could produce these radio emissions, namely mode conversion at f_p and $2f_p$ from Langmuir waves excited by a shock [see Cairns et al., 1992]. To decide between a source at the terminal shock and a source at the heliopause, it is necessary to consider the radial variation of f_p. For a constant solar wind velocity, it is easy to show that the electron plasma frequency must vary inversely with distance from the Sun ($f_p \sim 1/R$). A representative radial variation of f_p is shown in Figure 6. Since an average value for f_p at 1 AU is 20 kHz, the electron plasma frequency at 100 AU should be about 200 Hz. According to conventional MHD theory, the jump in the plasma frequency at the terminal shock can be no more than a factor of two. Thus, the maximum plasma frequency at the terminal shock should be about 400 Hz. This plasma frequency is too low to account for radio emissions at 2-3 kHz. Thus, it is believed that an interaction at the terminal shock cannot account for the heliospheric 2-3 kHz radio emission. The only known way in which the terminal shock could be the source would be if the density jump substantially exceeds the MHD limit due to the effect of cosmic rays, as has been suggested by Donohue and Zank [1993], or if the terminal shock were to be located much closer than 100 AU, which would invalidate the cause-effect relationship suggested by Figure 5.

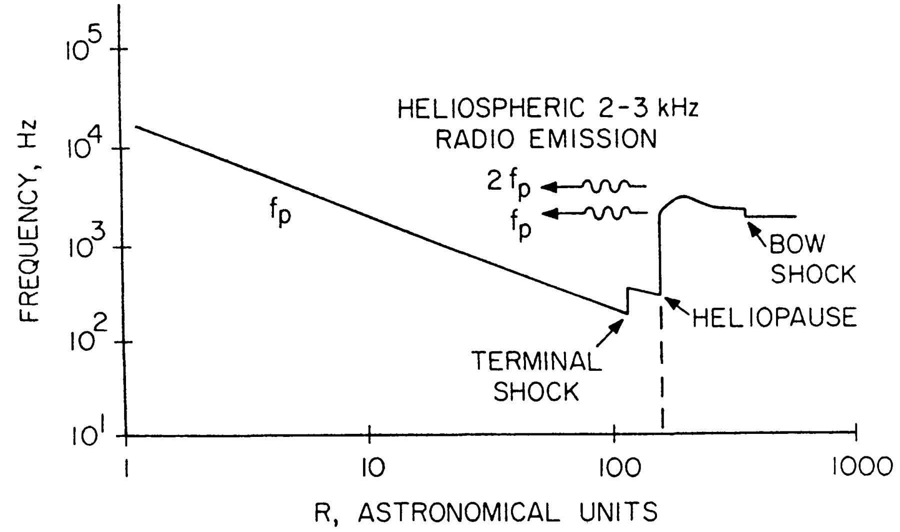

Fig. 6. A representative electron plasma frequency profile through the terminal shock, the heliopause, and the bow shock. Using nominal parameters the heliopause is believed to be the most likely source of the 2-3 kHz radiation, since the plasma frequency is too low in the vicinity of the terminal shock.

At the heliopause, the situation is much more favorable for generating radio emissions in the required frequency range. Since the heliopause is a contact discontinuity, the density can increase by whatever factor is required to maintain pressure balance. Present estimates are that the electron density in the local interstellar medium is in the range from 0.06 to 0.1 cm^{-3} [Lallement et al., 1993]. Since the bow shock is expected to be a weak shock, the interstellar electron density in the vicinity of the heliopause should be approximately 2.2 to 2.8 kHz. This plasma frequency is consistent with the frequency range of the 2-3 kHz radio emissions. For this reason, Gurnett et al. [1993b] proposed that the 1983-84 and 1992-93 heliospheric radio emission events were caused by an interaction involving the heliopause and the interplanetary shocks responsible for the giant Forbush decreases observed in 1982 and 1991. For propagation speeds in the range from 550 to 800 km/s, which are consistent with the available observations, and a travel time of $\sim$400 days, the radial distance to the heliopause is estimated to be in the range from 106 to 177 AU. The corresponding distances to the terminal shock are about 80 to 133 AU.

V. Prospects for Future Progress

The forthcoming passage of the Ulysses spacecraft over the poles of the Sun and the continued progress of Voyagers 1 and 2 to greater distances from the Sun are both likely to lead to significant advances in our understanding of heliospheric radio emissions. The ability of the Ulysses plasma wave instrument to capture and store Langmuir wave amplitudes on time scales of 1 ms, or less, is an important capability that may lead to a better understanding of the fine structure of Langmuir waves, and the generation of type II and type III radio emissions. The two-dimensional radio direction-finding capability of Ulysses [Stone et al., 1992] will provide a unique capability for studying the latitudinal dependence of solar radio bursts as the spacecraft passes over the poles of the Sun. This direction-finding capability would also be of great interest for studying the heliospheric 2-3 kHz radio emissions. Although the average electron plasma frequency at the Ulysses orbit appears to be too high to allow the detection of the 2-3 kHz radiation, if the spacecraft passes through a region of sufficiently low plasma density ($f_p < 3.6$ kHz), every effort should be made to detect these emissions.

References

Anderson, K.A., Lin, R.P., Martel, F., Lin, C.S., Park, G.K., and Reme, H.: 1979, 'Thin sheets of energetic electrons upstream from the Earth's bow shock', *Geophys. Res. Lett.* **6**, 401-404.

Axford, W.I., 1990: 'Introductory Lecture - The Heliosphere', in S. Grzedzielski and D.E. Page (eds.), *Physics of the Outer Heliosphere*, COSPAR Colloquia Series, **1**, Pergamon Press, Oxford, p. 7-15.

Cairns, I.H., and Robinson, P.A.: 1992, 'Theory for low-frequency modulated Langmuir wave packets', *Geophys. Res. Lett.* **19**, 2187-2190.

Cairns, I.H., Kurth, W.S., and Gurnett, D.A.: 1992, 'Outer heliospheric radio emissions, 2. Foreshock source models', *J. Geophys. Res.* **97**, 6245-6259.

Donohue, D.J., and Zank, G.P.: 1993, 'Steady state and dynamical structure of a cosmic-ray-modified termination shock', *J. Geophys. Res.* **98**, 19,005-19,025.

Dulk, G.A., Steinberg, J.-L., Hoang, S., and Lecacheux, A.: 1986, 'Latitude distribution of interplanetary magnetic field lines rooted in active regions', in R.G. Marsden (ed.), *The Sun and the Heliosphere in Three Dimensions*, D. Reidel Publising Company, 229-233.

Dunckel, N.: 1974, 'Low-frequency radio emissions from the Earth and Sun', *Tech. Rep. 3469-2*, Radioscience Laboratory, 114-131.

Fainberg, J., Evans, L.G., and Stone, R.G.: 1972, 'Radio tracking of solar energetic particles through interplanetary space', *Science* **178**, 743-745.

Filbert, P.C., and Kellogg, P.J.: 1979, 'Electrostatic noise at the plasma frequency beyond the Earth's bow shock', *J. Geophys. Res.* **84**, 1369-1381.

Ginzburg, V.L., and Zheleznyakov, V.V.: 1958, 'On the possible mechanism of sporadic solar radio emission (radiation in an isotropic plasma)', *Sov. Astron.* **AJ2**, 653.

Gosling, J.T.: 1993, 'The Solar Flare Myth', *J. Geophys. Res.* **98**, 18,937-18,949.

Grzedzielski, S., and Lazarus, A.J.: 1993, '2- to 3-kHz continuum emissions as possible indications of global heliospheric "breathing"', *J. Geophys. Res.* **98**, 5551-5558.

Gurnett, D.A., and Anderson, R.R.: 1976, 'Electron plasma oscillations associated with type III radio bursts', *Science* **194**, 1159-1162.

Gurnett, D.A., and Frank, L.A.: 1975, 'Electron plasma oscillations associated with Type III radio emissions and solar electrons', *Solar Physics* **45**, 477-493.

Gurnett, D.A., Hospodarsky, G.B., Kurth, W.S., Williams, D.J., and Bolton, S.J.: 1993a, 'Fine structure of Langmuir waves produced by a solar electron event', *J. Geophys. Res.* **98**, 5631-5637.

Gurnett, D.A., and Kurth, W.S.: 1994, 'Evidence that Jupiter is not the source of the 2-3 kHz heliospheric radio emission', *Geophys. Res. Lett.*, in press.

Gurnett, D.A., Neubauer, F.M., and Schwenn, R.: 1979, 'Plasma wave turbulence associated with an interplanetary shock', *J. Geophys. Res.* **84**, 541-552.

Gurnett, D.A., Kurth, W.S., Allendorf, S.C., and Poynter, R.L.: 1993b, 'Radio emission from the heliopause triggered by an interplanetary shock', *Science* **262**, 199-203.

Hoang, S., Fainberg, J., Steinberg, J.L., Stone, R.G., and Zwickl, R.D.: 1981, 'The $2f_p$ circumterrestrial radio radiation as seen from ISEE-3', *J. Geophys. Res.*, **86**, 4531-4536.

Hundhausen, A.J.: 1993, 'The size and location of coronal mass ejections: SMM observations from 1980 and 1984-89', *J. Geophys. Res.* **98**, 13,177.

Kaiser, M.L.: 1975, 'The solar elongation distribution of low-frequency radio bursts', *Solar Phys.* **45**, 181-187.

Kellogg, P.J., Goetz, K., Lin, N., Monson, S.J., Balogh, A., Forsyth, R.J., and Stone, R.G.: 1992, 'Low-frequency magnetic signals associated with Languir wave packets', *Geophys. Res. Lett.* **19**, 1299.

Kennel, C.F., Scarf, F.L., Coroniti, F.V., Smith, E.J., and Gurnett, D.A.: 1982, 'Nonlocal plasma turbulence associated with interplanetary shocks', *J. Geophys. Res.* **87**, 17-34.

Krall, N.A., and Trivelpiece, A.W.: 1973, *Principles of Plasma Physics*, McGraw-Hill, New York.

Kurth, W.S., and Gurnett, D.A.: 1991, 'New observations of the low frequency interplanetary radio emissions', *Geophys. Res. Lett.* **18**, 1801-1804.

Kurth, W.S., Gurnett, D.A., Scarf, F.L., and Poynter, R.L.: 1984, 'Detection of a radio emission at 3 kHz in the outer heliosphere', *Nature* **312**, 27-31.

Kurth, W.S., Gurnett, D.A., Scarf, F.L., and Poynter, R.L.: 1987, 'Long-period dynamic spectrograms of low-frequency interplanetary radio emissions', *Geophys. Res. Lett.* **14**, 49-52.

Lallement, R., Bertaux, J.-L., and Clark, J.T.: 1993, 'Deceleration of interstellar hydrogen at the heliospheric interface', *Science* **260**, 1095-1098.

Lengyel-Frey, D.: 1992, 'Location of the radio emitting regions of interplanetary shocks', *J. Geophys. Res.* **97**, 1609-1617.

Lin, R.P.: 1970, 'The emission and propagation of 40 keV solar flare electrons', *Solar Phys.* **12**, 266.

Lin, R.P., Levedahl, W.K., Lotko, W., Gurnett, D.A., and Scarf, F.L.: 1986, 'Evidence for nonlinear wave-wave interactions in solar type III radio burst', *Astrophys. J.* **308**, 954-965.

McNutt, R.L., Jr.: 1988, 'A solar-wind "trigger" for the outer heliospheric radio emissions and the distance to the terminal shock', *Geophys. Res. Lett.* **15**, 1307-1310.

Nelson, G.J., and Melrose, D.: 1985, 'Type II bursts', in D.J. McLean and N.R. Labrum (eds.), *Solar Radiophysics*, Cambridge University Press, Cambridge, 331-359.

Nelson, G.J., and Robinson, R.D.: 1975, 'Multi-frequency heliograph observations of type II bursts', *Proc. Astron. Soc. Aust.* **2**, 370.

Papadopoulos, K., and Freund, H.P.: 1978, 'Solitons and second harmonic radiation in type III bursts', *Geophys. Res. Lett.* **5**, 881-884.

Parker, E.N.: 1963, *Interplanetary Dynamical Process*, Interscience, Rochester, NY, 137.

Scarf, F.L., Fredricks, R.W., Frank, L.A., and Neugebauer, M.: 1971, 'Nonthermal electrons and high-frequency waves in the upstream solar wind: 1. Observations', *J. Geophys. Res.* **76**, 5162-5171.

Scarf, F.L., and Gurnett, D.A.: 1977, 'A plasma wave investigation for the Voyager mission', *Space Sci. Rev.* **21**, 289-308.

Stone, R.G., et al.: 1992, 'The unified radio and plasma wave investigation', *Astron. Astrophys. Suppl. Ser. 92*, 291-316.

Suess, S.T.: 1990, 'The heliopause', *Rev. Geophys.*, **28**, 97-115.

Van Allen, J.A., and Fillius, R.W.: 1992, 'Propagation of a large Forbush decrease in cosmic-ray intensity past the Earth, Pioneer 11 at 34 AU, and Pioneer 10 at 53 AU', *Geophys. Res. Lett.* **19**, 1423-1426.

Van Allen, J.A., and Randall, B.A.: 1985, 'Interplanetary cosmic ray intensity: 1972-1984 and Out to 32 AU', *J. Geophys. Res.* **90**, 1399-1412.

Wagner, W.J.: 1983, 'SERF studies of mass motions arising in flares', *Adv. Space Res.* **2**, 203.

Webber, W.R., and Lockwood, J.A.: 1993, 'Giant transient decreases of cosmic rays in the outer heliosphere in September 1991', *J. Geophys. Res.* **98**, 7821-7825.

Webber, W.R., Lockwood, J.A., and Jokipii, J.R.: 1986, 'Characteristics of large Forbush-type decreases in the cosmic radiation, 2. Observations at different radial distances', *J. Geophys. Res.* **91**, 4103-4110.

Wild, J.P.: 1950, 'Observations of the spectrum of high-intensity solar radiation at metre wavelengths, III, Isolated bursts', *Aust. J. Sci. Res. Ser. A*, **3**, 541.

Wild, J.P., Murray, J.D., and Rowe, W.C.: 1954b, 'Harmonics in the spectra of solar radio disturbances', *Aust. J. Phys.* **7**, 439.

Wild, J.P., Roberts, J.A., and Murray, J.D.: 1954a, 'Radio evidence of the ejection of very fast particles from the Sun', *Nature* **173**, 532.

Zakharov, V.E.: 1972, 'Collapse of Langmuir Waves', *Zh. Exp. Theoret. Fiz.* **62**, 1745, (English transl. in *Soviet Phys. - JETP* **35**, 908).