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Electron Plasma Oscillations Associated with Type III Radio Bursts

Abstract. *Plasma wave electric field measurements with the solar orbiting Helios spacecraft have shown that intense (approximately 10 millivolts per meter) electron plasma oscillations occur in association with type III solar radio bursts. These observations confirm the basic mechanism, proposed in 1958, that type III radio emissions are produced by intense electron plasma oscillations excited in the solor corona by electrons ejected from a solar flare.*

Plasma wave electric field instruments on the German-American Helios 1 and Helios 2 spacecraft, in orbit around the sun, have detected intense electron plasma oscillations in association with type III solar radio bursts. These observations confirm a well-known mechanism, proposed by Ginzburg and Zheleznyakov (*1*) in 1958, for the generation of these radio emissions. In this report we briefly describe the essential features of the plasma oscillation mechanism for generating type III radio bursts and present the recent Helios results, which show the occurrence of intense electron plasma oscillations in association with type III radio bursts.

Type III radio bursts are produced by particles ejected from a solar flare and are characterized by an emission frequency which decreases with increasing time. These radio bursts are observed over a very broad frequency range, from as high as several hundred megahertz to as low as 10 khz. The characteristic frequency variation of type III radio bursts was explained by Wild (*2*) in 1950, who proposed that the radio emissions are generated at a local oscillation frequency of plasma in the solar corona called the electron plasma frequency: $f_p^- = 9n^{1/2}$ (khz), where n is the electron density (cm^{-3}). The decreasing emission frequency with increasing time is attributed to the decreasing electron density, hence plasma frequency, encountered by the solar flare particles as they move outward through the solar corona and solar wind. Measurements with satellite-borne instruments have shown that the particles responsible for the type III radio emissions are electrons with energies ranging from a few kiloelectron volts to several tens of kiloelectron volts (*3*).

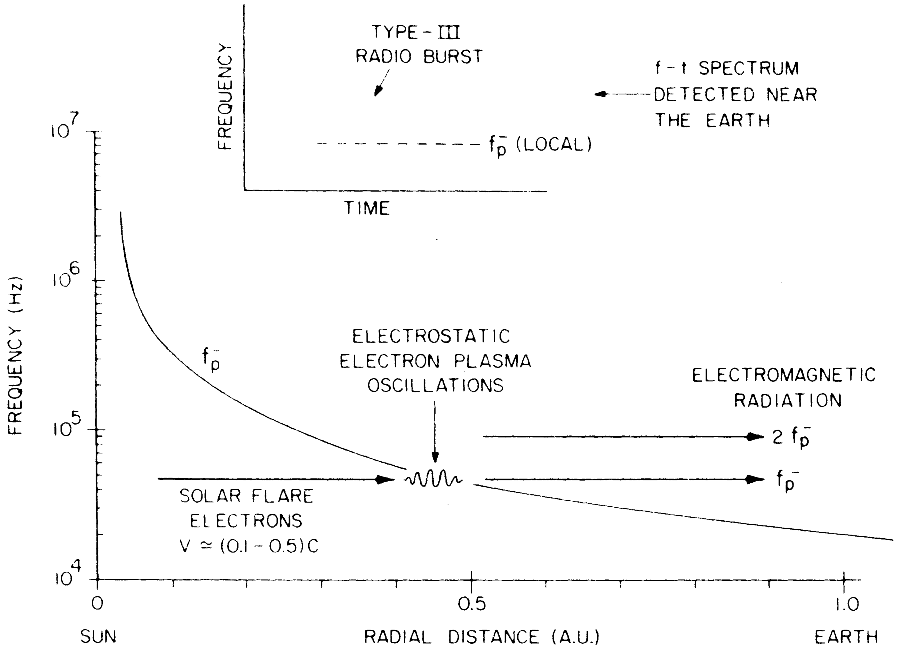

Fig. 1. Radial variation of the electron plasma frequency, f_p^-, between the sun and the earth. Type III solar radio bursts are believed to be generated by a two-step process in which (i) localized electron plasma oscillations at f_p^- are produced by solar flare electrons streaming outward from the sun, and (ii) these plasma oscillations are converted to escaping electromagnetic radiation by nonlinear wave-wave interactions. The characteristic frequency variation of the type III burst is caused by the decreasing plasma frequency encountered by the solar flare electrons as they move away from the sun. Abbreviations: v, electron velocity; c, speed of light.

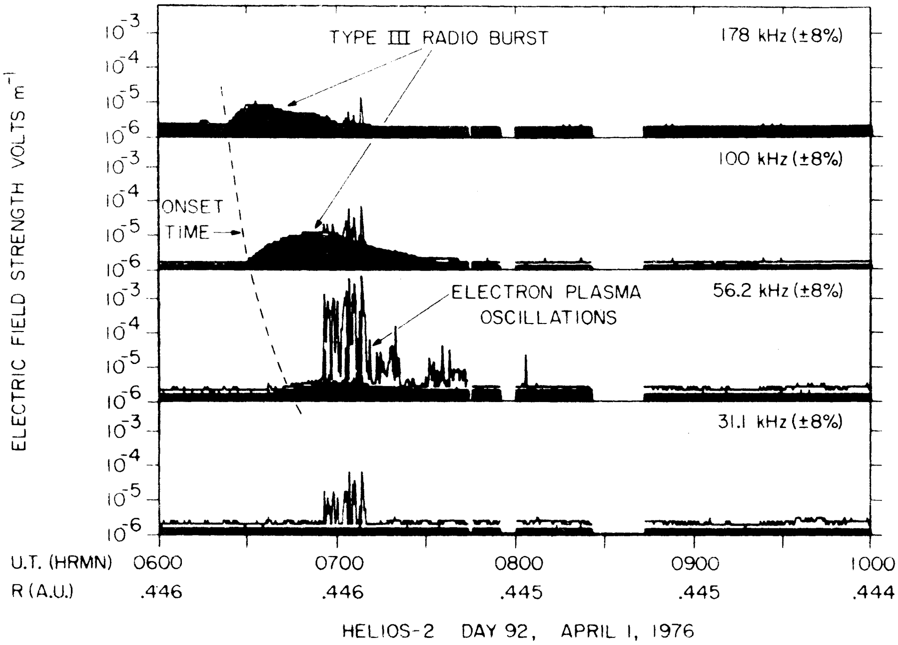

Fig. 2. Example of the intense electron plasma detected by Helios 2 in association with a type III solar radio burst. Note the characteristic increasing onset time of the type III burst with decreasing frequency and the narrow bandwidth of the electron plasma oscillations in the 56.2-khz channel. The electron plasma frequency determined by the solar-wind plasma experiment on Helios is $f_p^- = 54$ khz, which is very close to the observed frequency of the electron plasma oscillations. The solid lines give the peak electric field intensities, and the solid black area indicates the average intensities.

According to the mechanism proposed by Ginzburg and Zheleznyakov, and subsequently refined and modified by other investigators (*4*, *5*), the generation of type III radio emissions is a two-step process in which (i) electrostatic plasma oscillations are first produced at the local electron plasma frequency by a two-stream instability excited by the solar flare electrons, and (ii) the plasma oscillations are converted to electromagnetic radiation by nonlinear wave-wave interactions. This mechanism is illustrated schematically in Fig. 1, which shows a model for the radial variation of the electron plasma frequency from the sun to the earth. According to current ideas, the electrostatic energy of the plasma oscillations is transformed into electromagnetic radiation at either the fundamental (f_p^-) or the harmonic ($2f_p^-$) of the local electron plasma frequency. The radiation at the fundamental is caused by interactions of the plasma oscillations with ion sound waves, and the radiation at the second harmonic is caused by interactions between oppositely propagating electron plasma oscillations. Radiation at both the fundamental and the harmonic has been detected, although at low frequencies ($\lesssim$ 1 Mhz) the harmonic radiation appears to be the dominant component (*6*).

Since the electron plasma oscillations are local phenomena and cannot be detected remotely, in situ measurements must be obtained in the solar corona or solar wind to confirm the occurrence of these oscillations in association with type III bursts. Rough estimates, using the theoretical model of Papadopoulos *et al.* (*5*), indicate that plasma oscillations with field strengths of about 10 mv m^{-1} or larger are required to explain the power flux of a typical type III radio burst at low frequencies (*7*). Although it should be possible to detect such plasma oscillations in the solar wind with earth-orbiting satellites, considerable difficulty has been experienced in obtaining confirming observations. After nearly 4 years of measurements with the earth-orbiting IMP 6 and IMP 8 satellites, no electron plasma oscillations with intensities this large have been found in association with a type III radio burst (*7*). This difficulty can be attributed to two factors. First, since the plasma oscillations occur only in the source, whereas the type III radiation propagates over large distances, electron plasma oscillations are expected to be detected for only a small fraction of the observable type III radio bursts. If the source region is very small or filamentary, as appears to be the case, then it is very improbable that the spacecraft will be suitably located within the beam of electrons ejected by the flare to detect the plasma oscillations. Second, and probably more important, for satellite observations near the earth it is very difficult to distinguish plasma oscillations generated by electrons from a solar flare from similar plasma oscillations (*8*) generated in the vicinity of the earth by electrons emitted from the earth's bow shock. The noisy and very disturbed plasma environment near the earth makes it very difficult to identify the plasma oscillations expected in association with a type III radio burst.

The solar orbiting Helios 1 and Helios 2 spacecraft provided the first opportunity to obtain simultaneous measurements of plasma waves and radio emissions away from the disturbing effects of the earth and in the region close to the sun, where the solar radio bursts are most intense. These spacecraft were launched on 10 December 1974 and 15 January 1976 into eccentric orbits near the ecliptic plane with perihelion radial distances of 0.309 and 0.290 A.U., approaching closer to the sun than any previous spacecraft. The plasma wave and radio astronomy instrumentation on the Helios spacecraft consists of a 32-m electric dipole antenna and a combination of frequency spectrum analyzers provided by the University of Iowa, the University of Minnesota, and Goddard Space Flight Center. A more detailed description of this instrumentation is provided by Gurnett and Anderson (*9*).

During the first 18 months after the launch of Helios 1, a total of 24 type III radio bursts was detected by the two Helios spacecraft. Of these, three events have been found with unusually intense electron plasma oscillations, which are almost certainly associated with the type III radio emission. The basic parameters for these events are summarized in Table 1. All three of these events were detected by Helios 2 within a single 24-hour interval from 31 March to 1 April 1976, during a period of exceptional solar flare activity which lasted from 23 March to 2 April 1976. At the time of these events Helios 2 was at a radial distance of about 0.45 A.U. from the sun and in a position which placed the spacecraft within, or very near, the source region of the type III radio emission.

Table 1. Type III radio bursts associated with intense electron plasma oscillations detected by Helios 1 and Helios 2 spacecraft. The values in the last column are the plasma oscillation field strengths required to account for the observed radio emission intensities; they were computed by using the theory of Papadopoulos *et al.* (*5*) with $\alpha = 0.1$, $n = 36$ electron/cm^3, $T_e = 10$ ev, and $R = 0.44$ A.U. [see (*7*) for details of these calculations].

Type III burst				Electric field strength of plasma oscillations (mv m^{-1})	
Date (1976)	U.T.	Intensity at $2f_p^- \simeq 100$ khz (watt m^{-2} hertz^{-1})	f_p^- (khz)	Observed	Calculated
31 March	1810	1.15×10^{-17}	58	14.8	6.01
1 April	0620	2.59×10^{-17}	54	5.26	7.37
1 April	1038	8.17×10^{-17}	56	2.35	9.82

The detailed electric field intensities for one of these events are shown in Fig. 2. The type III radio emission can be clearly seen in the 178- and 100-khz channels and is just barely detectable in the 56.2-khz channel. The smooth intensity variation and the increase of onset time with decreasing frequency provide a unique identification of this event as a type III radio burst. Starting at about 0655 U.T., and lasting to about 0720 U.T., a series of intense bursts of electric field noise is evident in the 56.2-khz channel. These bursts are very intense, reaching a peak electric field strength of 5.26 mv m^{-1}. This intensity is almost 60 db greater than the corresponding intensity of the type III radio emission in this channel. Comparisons with the solar wind plasma density measurements from Helios (*10*) show that the center frequency of these bursts, $\sim$ 56.2 khz, is very close to the local electron plasma frequency, $f_p^- = 54$ khz. The bandwidth of these bursts is evidently very narrow, since the corresponding weak bursts in the adjacent 31.1- and 100-khz channels can be completely attributed to the frequency response of the spectrum analyzer filters, assuming a nearly monochromatic emission at $f_p^- \simeq 54$ khz. The narrow bandwidth of the bursts and the close agreement of the emission frequency with the local electron plasma frequency provide convincing evidence that this electric field noise consists of electron plasma oscillations. The very close temporal correspondence between the occurrence of these plasma oscillations and the occurrence of the type III radio burst leaves essentially no doubt that the plasma oscillations are associated with the type III emission. A qualitatively similar relationship is also observed for the remaining two events.

The peak electric field strengths of the three intense plasma oscillation events detected by Helios and the corresponding type III radio emission intensities at $2f_p^- \simeq 100$ khz are summarized in Table 1. For comparison, the computed plasma oscillation field strengths required to account for the observed radio emission intensities are also shown in Table 1. These electric field intensities have been calculated by using the theoretical model of Papadopoulos *et al.* (*5*) for the conversion of the plasma oscillation energy to electromagnetic radiation. Further details of the assumptions used in these calculations are given by Gurnett and Frank (*7*). As can be seen from Table 1, the observed plasma oscillation field strengths are in excellent quantitative agreement with the field strengths required by the theory.

The Helios observations have provided a firm confirmation that the basic plasma oscillation mechanism proposed by Ginzburg and Zheleznyakov is involved in the generation of type III radio emissions. However, many important questions still remain. Since intense plasma oscillations of the type detected by Helios are rarely observed compared to the number of type III radio bursts detected at the earth (*7*), it is generally concluded that the spatial distribution of plasma oscillations must be highly inhomogeneous, with the intense plasma oscillations confined to small isolated regions. Since the power radiated by the plasma oscillations is a very strong function (fourth power) of the electric field strength, the fraction of the total volume containing plasma oscillations could be quite small, < 1 percent, with only a moderate increase in the required field strengths. For each of the three cases detected by Helios the plasma oscillations are extremely impulsive, consisting of many short bursts lasting for only a few seconds or less. These impulsive variations are clearly indicated by the large ratio of the peak to average field strengths evident in Fig. 2. The highly inhomogeneous structure indicated by these variations was not contemplated in the original model of Ginzburg and Zheleznyakov, which only dealt with the linear growth of the plasma oscillations, and has been studied only recently (5) in relation to the large-amplitude nonlinear evolution of the two-stream instability. Considerable further investigation, both theoretical and experimental, is still required to fully understand the spatial structure of these intense plasma oscillations and the implications with regard to the generation of radio emissions by the sun and other cosmic radio sources.

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