

# The Heliocentric Radial Variation of Plasma Oscillations Associated With Type III Radio Bursts

D. A. GURNETT, R. R. ANDERSON, F. L. SCARF,<sup>1</sup> AND W. S. KURTH

*Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242*

A survey is presented of all of the electron plasma oscillation events found to date in association with low-frequency type III solar radio bursts using approximately 9 years of observations from the Imp 6 and 8, Helios 1 and 2, and Voyager 1 and 2 spacecraft. Plasma oscillation events associated with type III radio bursts show a pronounced increase in both the intensity and the frequency of occurrence with decreasing heliocentric radial distance. This radial dependence explains why intense electron plasma oscillations are seldom observed in association with type III radio bursts at the orbit of the earth. Possible interpretations of the observed radial variation in the plasma oscillation intensity are considered.

## 1. INTRODUCTION

The currently accepted model for the generation of type III solar radio bursts is that these radio emissions are produced by nonlinear processes involving electron plasma oscillations excited by solar flare electrons streaming outward through the solar corona. The electron plasma oscillation mechanism, first proposed by *Ginzburg and Zheleznyakov* [1958], has become the basic element of essentially all theories of type III radio bursts, with suitable refinements to account for various types of nonlinear interactions [*Sturrock*, 1961; *Tidman et al.*, 1966; *Papadopoulos et al.*, 1974; *Smith*, 1974]. Although the plasma oscillation mechanism has been widely accepted for many years, only in the past two years have measurements been obtained which definitely establish the existence of these electron plasma oscillations. Initially, studies by earth-orbiting satellites failed to detect electron plasma oscillations in association with type III radio bursts [*Kellogg and Lin*, 1976]. After searching through nearly 4 years of data from the earth-orbiting Imp 6 and 8 satellites, only one type III event was identified with clearly associated electron plasma oscillations [*Gurnett and Frank*, 1975]. However, the intensity of this event,  $\sim 100 \mu\text{V m}^{-1}$ , was much too small to account for the observed radio emission intensities. The first observations of electron plasma oscillations with intensities sufficiently large to explain type III radio emissions were obtained from the Helios 1 and 2 solar probes, in orbit around the sun at radial distances ranging from 0.29 to 1.00 AU [*Gurnett and Anderson*, 1976, 1977]. In the initial survey of the Helios 1 and 2 plasma wave data, three events were found with electron plasma oscillation intensities exceeding  $1 \text{ mV m}^{-1}$ . All of these events occurred relatively close to the sun, at heliocentric radial distances of less than 0.45 AU.

Since the initial survey of the Helios 1 and 2 data the quantity of data available for analysis has increased considerably, and several more intense electron plasma oscillation events have been identified in association with type III radio bursts. Approximately 12 months of plasma wave data are also available from the Voyager 1 and 2 spacecraft at radial distances of from 1.0 to 2.2 AU. A description of the plasma wave instrumentation on the Voyager 1 and 2 spacecraft is given by *Scarf and Gurnett* [1977]. From these data it is found that the most intense electron plasma oscillations,  $\sim 1\text{--}10 \text{ mV m}^{-1}$ , are

usually detected relatively close to the sun, at heliocentric radial distances of less than 0.5 AU, and that only weak events,  $\sim 100 \mu\text{V m}^{-1}$ , are detected near and beyond 1.0 AU. These observations indicate the presence of a strong radial variation in the electron plasma oscillation intensities associated with type III radio bursts, decreasing rapidly with increasing radial distance from the sun. The purpose of this paper is to survey the characteristics of all of the electron plasma oscillation events observed to date in association with type III bursts and to investigate the variation in intensity of these events with radial distance from the sun.

## 2. SURVEY OF EVENTS ANALYZED

Up to the present time a total of 18 type III solar radio bursts have been detected with clearly associated electron plasma oscillations. The total quantity of data surveyed to identify these events consists of approximately 4 years of observations from Imp 6 and 8 [*Gurnett and Frank*, 1975], 4 years of observations from Helios 1 and 2, and 12 months of observations from Voyager 1 and 2. These data include 153 type III radio bursts which were detectable at frequencies below 178 kHz. Since only 18 of these events occur in association with plasma oscillations, it is evident that the chance of detecting the plasma oscillations responsible for a type III radio burst is quite small, approximately 12%.

The typical characteristics of the events detected are illustrated in Figures 1 and 2, which show the electric field strength in four adjacent frequency channels for each of the 18 events. The solid line in each plot gives the maximum electric field strength, and the solid black area (or vertical lines in the case of days 208 and 209) gives the average electric field strength. The spectrum analyzers on Imp 6, Imp 8, Helios 1, and Helios 2 all have continuously active channels with peak detection so that any signal within the time resolution of the instrument ( $\sim 50 \text{ ms}$ ) is always detected by the peak field strength measurement. The maximum field strength shown in each channel is the largest peak field strength in the interval since the previous point plotted. For Voyager 1, which does not have peak detection, the maximum field strength is computed from all of the average field strengths available in each interval plotted. The type III radio bursts in Figures 1 and 2 are in most cases easily identified by the smooth increase in the field strength over a period of several tens of minutes and by the characteristic decrease in the emission frequency with increasing time. The electron plasma oscillations associated with these events usually consist of a series of brief but very intense narrow band

<sup>1</sup> Now at TRW Defense and Space Systems Group, Redondo Beach, California 90278.

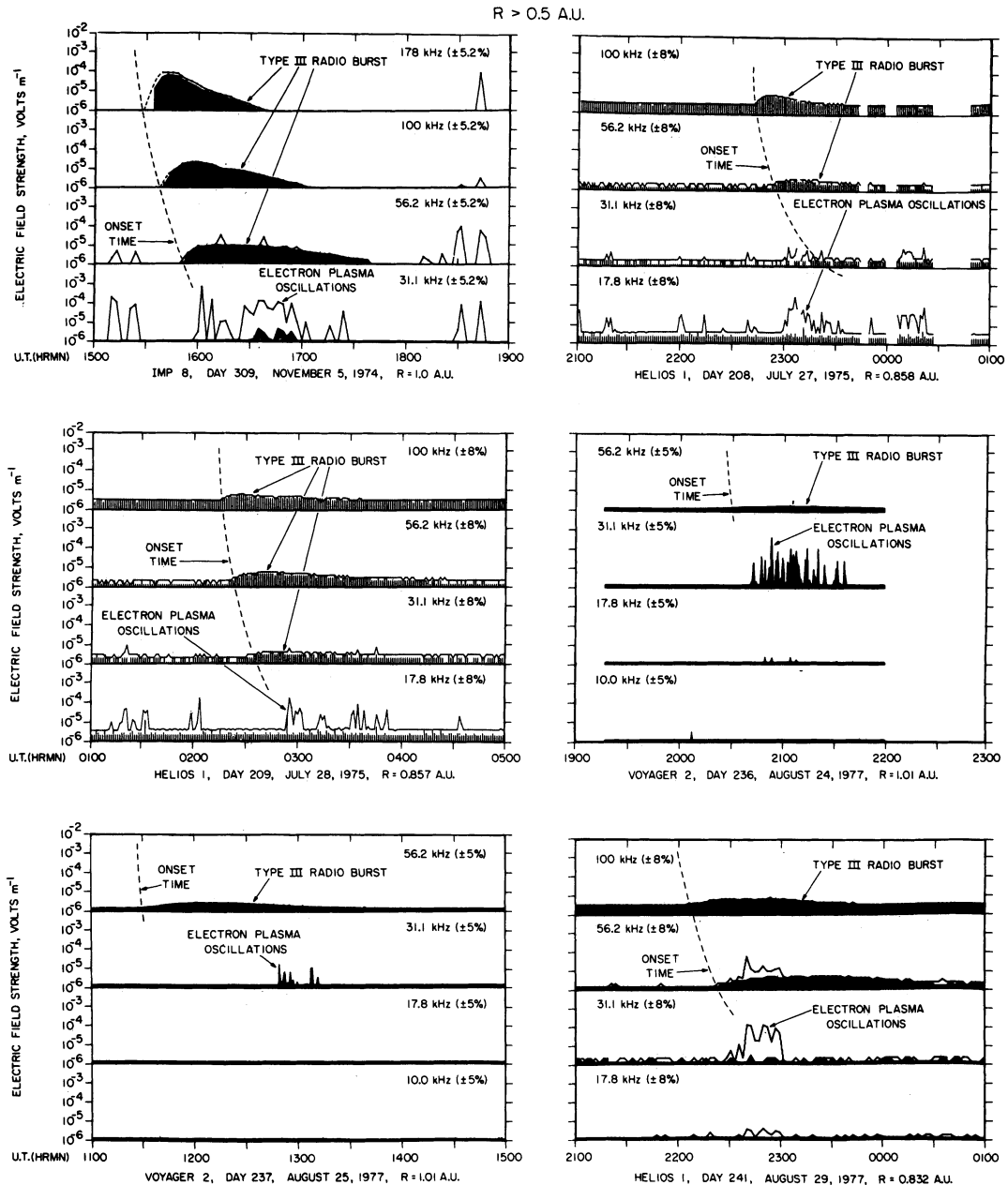


Fig. 1a

Fig. 1. All of the type III radio noise bursts and associated electron plasma oscillation events observed to date at heliocentric radial distances beyond 0.5 AU. The solid line gives the maximum electric field intensity, and the solid black areas (or vertical bars for days 208 and 209) give the average electric field intensity. The plasma oscillations beyond 0.5 AU are generally very weak, typically  $\sim 100 \mu\text{V m}^{-1}$ , and occur very infrequently in comparison with the total number of type III bursts.

bursts at the local electron plasma frequency. These bursts usually occur shortly after the onset of the type III radio emission in the next higher frequency channel. The maximum electric field intensity is always much larger than the average electric field intensity, indicating that the plasma oscillations consist of many short impulsive bursts. The impulsive intensity variations of the plasma oscillations are illustrated in greater detail in Figure 3, which shows a high-time resolution snapshot of the plasma oscillation intensities associated with the day 92, 1976, event. The most intense burst detected during this interval lasted only a few tenths of a second. Large temporal variations are evident on time scales comparable to the time resolution (50 ms) of the instrument.

To illustrate the variation in plasma oscillation intensity with heliocentric radial distance, the events in Figures 1 and 2 have been arranged with all of the events at radial distances greater than 0.5 AU in Figure 1 and all of the events at radial distances less than 0.5 AU in Figure 2. Comparison of these illustrations shows that the plasma oscillations are more intense in the region closer to the sun. Although more events have been detected beyond 0.5 AU than inside of 0.5 AU, considerations of the relative observing times in the two regions show that the frequency of occurrence of plasma oscillations is significantly higher in the region closer to the sun. Because of the eccentric orbits of the Helios spacecraft, with aphelion near 1.0 AU and perihelion near 0.3 AU, the frac-

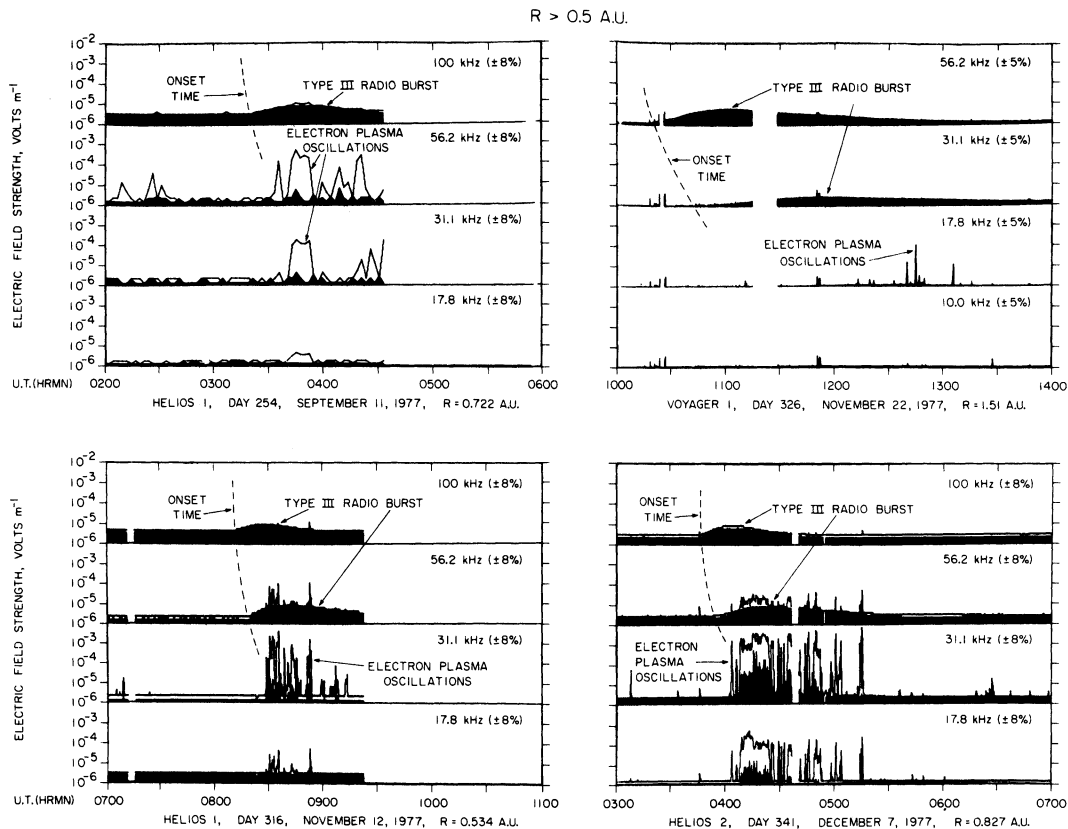


Fig. 1b

tional observing time inside of 0.5 AU is only about 25%. It is estimated that only about 1 year of total observing time is available inside of 0.5 AU, compared with 8 years of combined observing time outside of 0.5 AU. Since eight events have been detected in only 1 year at  $R \leq 0.5$  AU, compared with ten events in 8 years at  $R > 0.5$  AU, we estimate that the chance of detecting plasma oscillations in association with a type III radio burst is almost 10 times larger in the region inside of 0.5 AU than in the region beyond 0.5 AU.

As can be seen from Figure 1, most of the plasma oscillation events beyond 0.5 AU are quite weak, typically only a few hundred microvolts per meter. In many of these cases it is probably questionable whether these weak plasma oscillations could be responsible for the observed radio emission intensities, even though the close time coincidence indicates that they are produced by the same particles which are responsible for the type III radio emission. Probably the only events in Figure 1 which are strong enough to account for the observed type III radio emission intensities, according to current theories, are on days 316 and 341, 1977. As is evident in Figure 2, the plasma oscillations inside of 0.5 AU are generally much more intense, typically 1–10  $mV m^{-1}$ . According to the estimates of Gurnett and Frank [1975], plasma oscillations in this intensity range are required to explain the observed type III radio emission intensities. For the intense events the onset of the plasma oscillations is usually very abrupt, as it is on days 92, 108, 112, 278, and 279, and consistently occurs about 10–30 min after the onset of the radio burst in the next higher frequency channel. Detailed comparisons show, however, that the onset time is usually a little too late to be consistent with generation of the type III radio emission at the second harmonic of the electron plasma frequency [Fainberg and Stone, 1974; Kaiser, 1975; Gurnett et al., 1978]. If the radiation is

generated at the second harmonic, as is widely believed, then the plasma oscillations should start when the frequency of the type III radio emission reaches the second harmonic,  $2f_p^-$ , of the local electron plasma frequency. As can be seen for the events on days 91, 92, 108, 112, and 341, the plasma oscillations start well after the frequency of the type III emission drops below  $2f_p^-$ . The disagreement in these cases may indicate that the radiation was being generated at the fundamental rather than the second harmonic, that plasma oscillations were present but on time scales too small ( $< 50$  ms) to be detected, or that the plasma oscillations were occurring in small regions or filaments which by chance were not encountered until well after the leading edge of the emission region had swept past the spacecraft. The events on day 341 in Figure 1 and day 108 in Figure 2 also show another interesting effect, which is a nearly constant peak electric field amplitude for time intervals of almost half an hour. These nearly constant electric field amplitudes are almost certainly the result of some nonlinear saturation mechanism which limits the maximum attainable electric field amplitude.

The radial variation of the maximum electric field amplitude with radial distance from the sun is shown in Figure 4. This illustration shows the maximum electric field amplitude for each of the 18 plasma oscillation events shown in Figures 1 and 2. A best fit power law through all of the points indicates that the electric field amplitude varies approximately as  $(1/R)^{3.5}$ . Although the limited number of events strongly restricts the accuracy with which the detailed radial dependence can be determined, the general trend toward decreasing field strength with increasing radial distance from the sun is unmistakable, especially when consideration is given to the much greater observing time near 1.0 AU compared with regions closer to the sun.

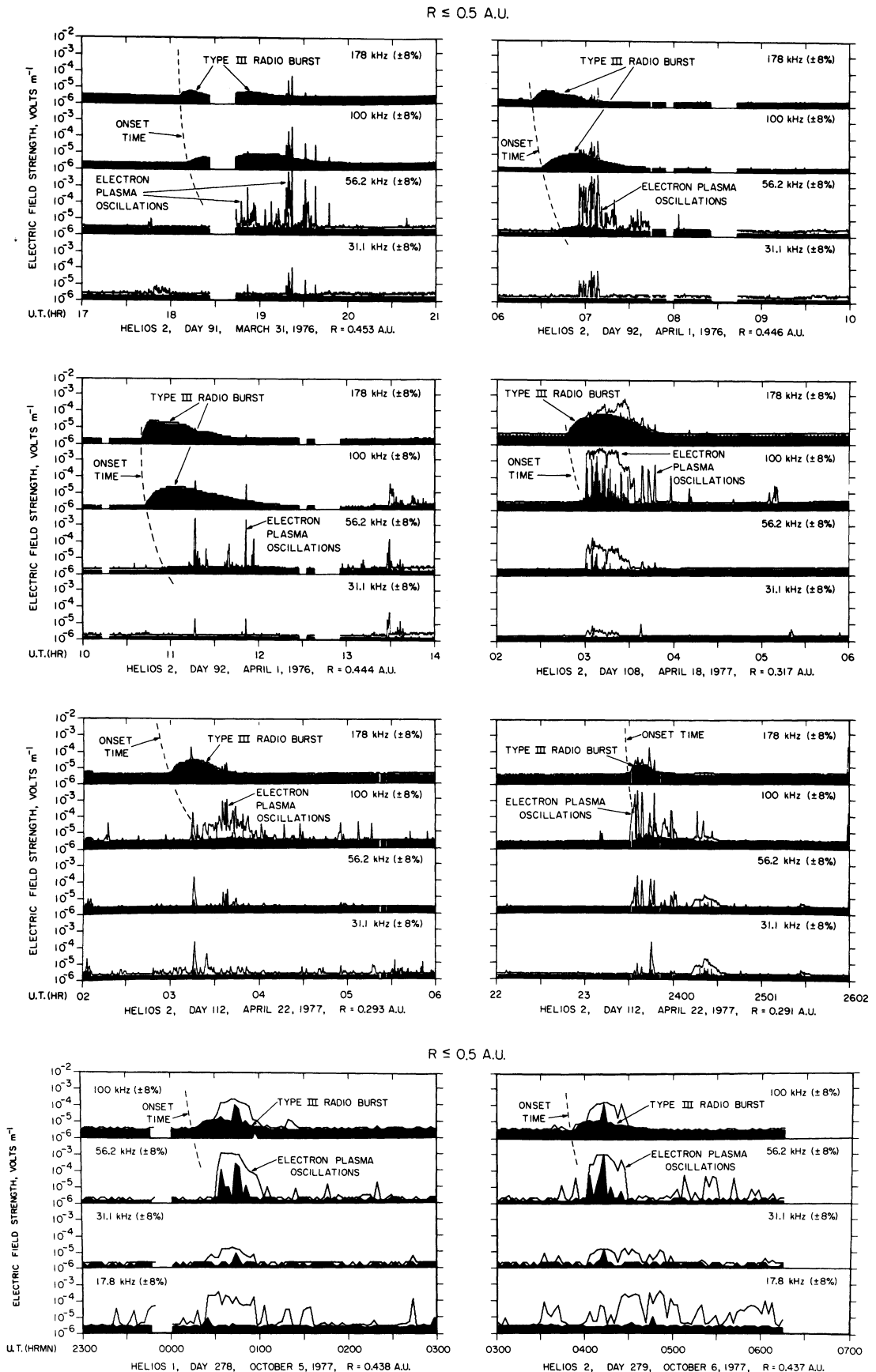


Fig. 2. All of the type III radio noise bursts and associated plasma oscillation events observed to date at heliocentric radial distances of less than 0.5 AU. The plasma oscillations closer to the sun, inside of 0.5 AU, are generally much more intense, typically 1–10  $mV m^{-1}$ , and occur much more frequently than those beyond 0.5 AU. Note the large ratio of the maximum (solid line) to the average (solid black area) field strength, indicating that the plasma oscillations consist of many brief impulsive bursts.

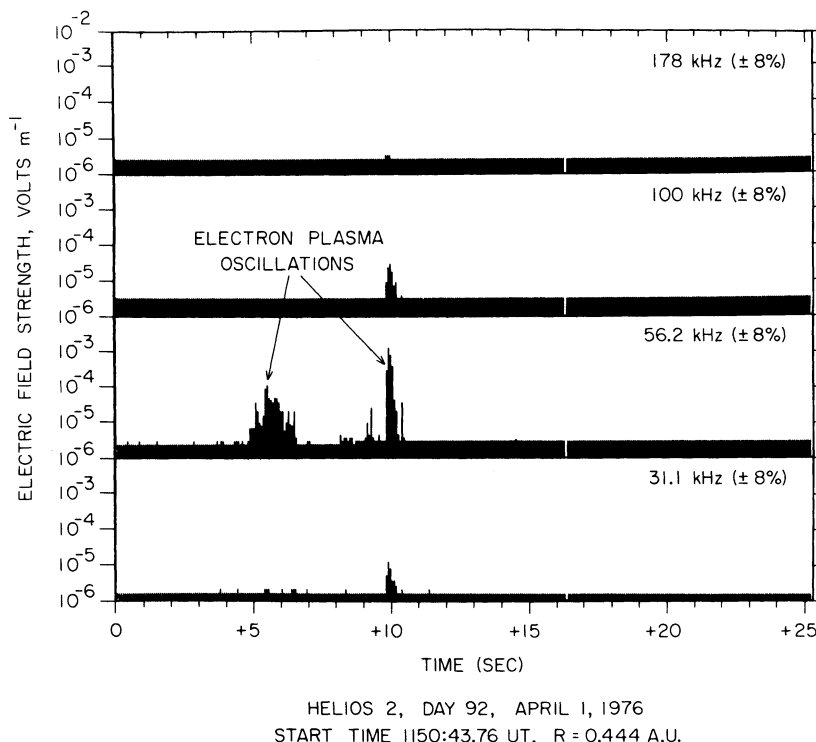


Fig. 3. A high-time resolution snapshot of the electron plasma oscillations associated with the event on day 92, 1976, in Figure 2. The plasma oscillations are seen to occur in short intense bursts lasting only a few tenths of a second. In some cases the temporal variations occur on time scales which approach the time resolution (50 ms) of the instrument.

### 3. DISCUSSION

These measurements show that the electric field strength of electron plasma oscillations associated with type III radio bursts decreases rapidly with increasing radial distance from the sun. This radial variation provides a partial answer to the question of why electron plasma oscillations are so seldom observed in association with type III radio bursts at the orbit of the earth. Evidently, by the time the beam of electrons which produces the type III radio emission reaches the earth, the velocity distribution function has evolved to the point that the plasma oscillations are only weakly unstable or not unstable at all. Closer to the sun the distribution function is evidently more unstable, leading to more intense plasma oscillations. The observed radial variation of plasma oscillation intensities is also consistent with the frequency spectrums of type III radio bursts, which usually decrease in intensity with decreasing frequency, indicating a decreasing emissivity (hence plasma oscillation intensity) with increasing radial distance from the sun.

Qualitatively, the decreasing plasma oscillation intensity with increasing distance from the sun fits in reasonably well with what one would expect, since the temporal dispersion of the emitted electron beam tends to intensify the unstable part of the electron velocity distribution function in the region closer to the sun, causing larger electric field amplitudes. A quantitative understanding of the observed radial variation, however, will require a detailed understanding of the nonlinear effects which saturate or limit the growth of the plasma oscillations and of the wave-particle interactions which influence the evolution of the electron beam as it propagates outward from the sun. Saturation effects are usually characterized by the dimensionless ratio of the electric field to plasma energy density,  $E^2/8\pi nkT$ , which for a given distribution function reaches an approximately constant asymptotic value after the instabil-

ity has grown into the nonlinear regime. Numerical simulations [Armstrong and Montgomery, 1967] for strongly unstable distributions typically show that after several hundred plasma periods the energy density ratio  $E^2/8\pi nkT$  approaches a constant asymptotic value characteristic of the initial beam intensity. Since the plasma density increases with decreasing distance from the sun approximately as  $n \propto (1/R)^2$  and the temperature  $T$  remains nearly constant, the electric field strength would be expected to vary as  $E \propto (1/R)$  if the asymptotic energy density ratio remains constant, independent of the radial distance. On the basis of the results in Figure 4 it is seen that the electric field strength varies much more rapidly than  $(1/R)$ , which means that changes in the electron beam characteristics are significantly modifying the asymptotic value of the saturation energy density ratio between 0.3 and 1.0 AU. Typical values for the energy density ratio vary from about  $E^2/8\pi nkT \approx 10^{-6}$  at 0.3 AU to about  $5 \times 10^{-9}$  at 1.0 AU.

Because of the complex evolution and interaction of the electron beam with the background plasma, numerical simulations are clearly needed to understand these radial dependences. Calculations of the propagation of solar electron streams have been performed by Magelssen and Smith [1977], assuming that the plasma oscillation intensities are controlled by quasi-linear interactions [Smith and Fung, 1971]. Overall, the results of Magelssen and Smith predict the correct general behavior, with approximately the right plasma oscillation amplitudes. However, detailed comparisons show significant disagreements with observations. The observed radial variation in the electric field energy density (in Figure 4) decreases more rapidly than predicted by the computer simulation, and the observed rapid spikelike variations in the plasma oscillation intensities have no resemblance to the smooth intensity variations predicted by the quasi-linear model. Further simulations using more complex models for the nonlinear beam plasma interactions, such as those discussed by Papadopoulos *et al.*

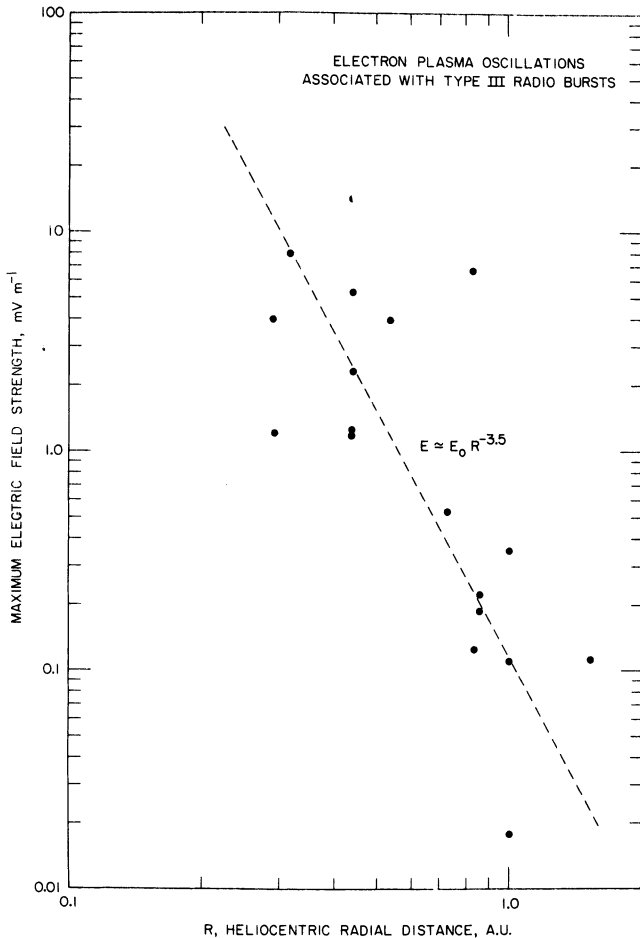


Fig. 4. A scatter plot of the maximum electric field strengths of the plasma oscillations in Figures 1 and 2 as a function of heliocentric radial distance. The electric field strength of the plasma oscillations decreases rapidly with increasing radial distance from the sun, varying approximately as  $R^{-3.5}$ .

[1974], Bardwell and Goldman [1976], and Rowland and Papadopoulos [1977], need to be performed to see if more complex models of the beam stabilization mechanism provide better agreement with the observations.

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