PLASMA OSCILLATIONS AND THE EMISSIVITY OF TYPE III RADIO BURSTS

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ABSTRACT

Plasma wave electric field measurements with the solar orbiting Helios spacecraft have shown that intense electron plasma oscillations occur in association with type III solar radio bursts, thereby confirming a well known mechanism for generating solar radio emissions first proposed by Ginzburg and Zheleznyakov in 1958. In this paper we review the principal characteristics of these plasma oscillations and compare the observed plasma oscillation intensities with recent measurements of the emissivity of type III radio bursts. The observed emissivities are shown to be in good agreement with two current models for the conversion of electrostatic plasma oscillations to electromagnetic radiation.

INTRODUCTION

As known from early studies of Wild [1950] 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. The decreasing emission frequency with increasing time is attributed to the decreasing electron plasma frequency, f_p^-, encountered by the solar flare particles as they move outward through the solar corona. Emission can occur at either the fundamental, f_p^-, or harmonic, $2f_p^-$, of the local electron plasma frequency, although at low frequencies, $\lesssim$ 1 MHz, the harmonic emission appears to be the dominant component [Fainberg, 1974; Kaiser, 1975; Gurnett et al., 1978]. The particles responsible for the type III radio emissions are electrons with energies ranging from a few Kev to several tens of Kev. According to current ideas, the generation of the type III radiation is a two-step process in which (i) electron plasma oscillations are first produced at f_p^- by a two-stream instability excited by the solar flare electrons and (ii) the plasma oscillations are converted to electromagnetic radiation by nonlinear wave-particle interactions. This mechanism, first proposed by Ginzburg and Zheleznakov [1958] and refined by numerous investigators [Tidman et al., 1966;

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Kaplan and Tystovich, 1968; Papadopoulos et al., 1974; Smith, 1977], is illustrated in Figure 1, which shows the expected conversion of the electron stream energy to electron plasma oscillations, and the subsequent conversion to electromagnetic radiation at either the fundamental, f_p^-, or the harmonic, $2f_p^-$. The radiation at the fundamental is caused by interactions of the plasma oscillations with ion sound waves, and the radiation at the harmonic is caused by interactions between oppositely propagating electron plasma oscillations.

Since electron plasma oscillations are local plasma wave phenomena which cannot be detected remotely, in situ measurements must be used to confirm the presence of these oscillations. The first observations of electron plasma oscillations associated with a type III solar radio burst were obtained by Gurnett and Anderson [1976, 1977] using measurements from the Helios 1 and 2 spacecraft which are in orbit around the sun between about 0.3 to 1.0 A.U. The Helios observations are important not only because they confirm a basic radio emission mechanism proposed over twenty years ago, but also because they provide important new information on nonlinear plasma processes of considerable current interest. In this paper we review the principal results of the Helios plasma oscillation observations, including many new events which have been recently detected. The plasma oscillation intensities are also compared with the recent type III radio emissivity measurements given by Tokar and Gurnett [1979], to provide a quantitative evaluation of proposed emission mechanisms.

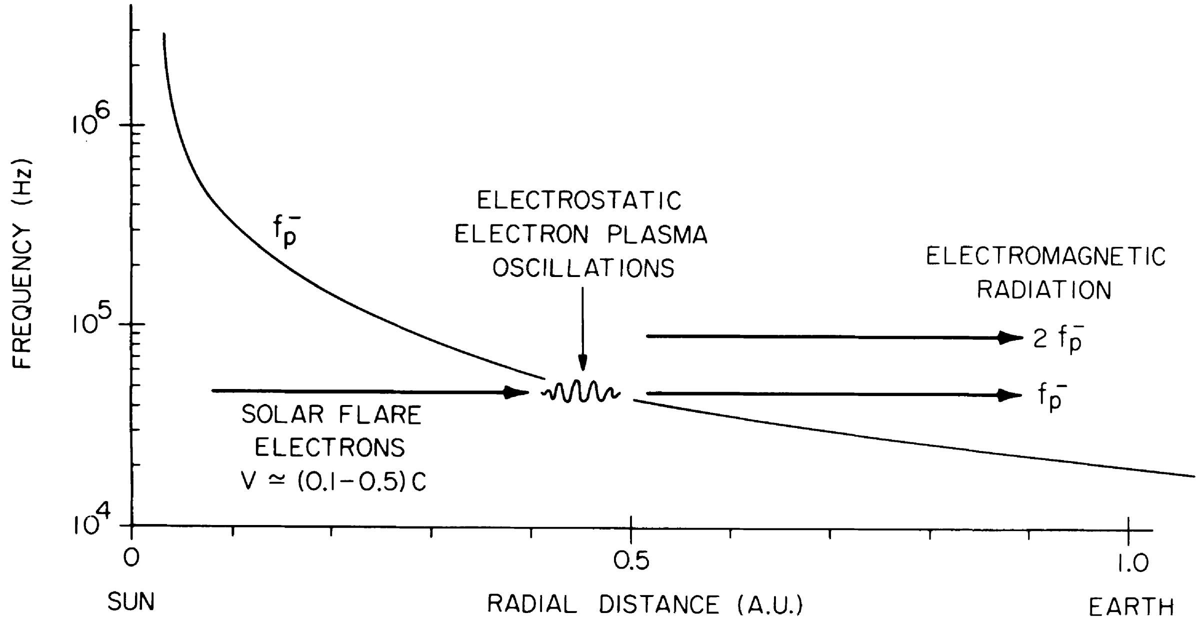

Figure 1. A representative radial profile of the electron plasma frequency in the solar wind illustrating the generation of electron plasma oscillations and the subsequent conversion to electromagnetic radiation at f_p^- and $2f_p^-$.

SURVEY OF PLASMA OSCILLATION CHARACTERISTICS

Only a small fraction, approximately 15%, of all the type III radio bursts detected by Helios can be associated with electron plasma oscillations. The relatively small occurrence of plasma oscillation events is almost certainly due to the fact that the radio emissions can be detected at large distances from the source, whereas the plasma oscillations can only be detected within the source region. Up to the present time a total of ninety electron plasma oscillation events have been identified in all the data available, which includes Helios 1 and 2, Voyager 1 and 2, and IMP 8. All but four of these events were detected by Helios 1 and 2.

A plasma oscillation event illustrating most of the features commonly observed is shown in Figure 2. The type III radio emission can be clearly identified in the 178 and 100 KHz channels by the rapid smooth rise to peak intensity followed by a somewhat longer smooth decay. The characteristic shift toward decreasing frequency with increasing time is also clearly evident. The intense narrow-band emissions in the 56.2 KHz channel, starting at about 1023 UT and ending about 1055 UT, are the associated electron plasma oscillations. The solid line is the peak

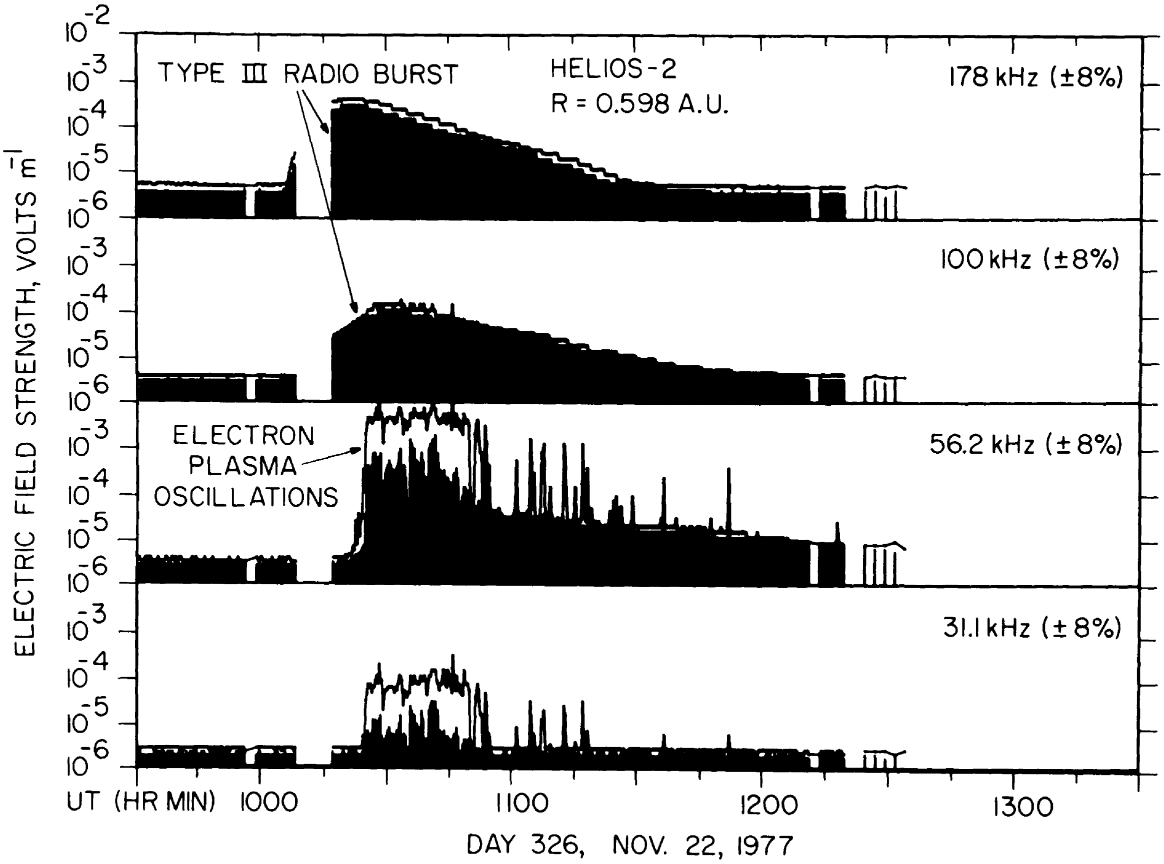

Figure 2. Intense electron plasma oscillations at $f_p^- \simeq 56$ kHz detected by Helios 2 in association with a type III radio burst.

electric field intensity and the solid dark area is the average electric field intensity. As can be seen the peak electric field intensity is much larger than the average electric field intensity indicating that the plasma oscillations are extremely impulsive, consisting of many short intense bursts. High time resolution measurements show that the bursts often occur on time scales approaching the time resolution of the instrument, which is about 50 msec. The occurrence of such short bursts has been suggested as indicating the presence of strong turbulence processes such as soliton collapse, which would occur on spatial scales of only a few Debye lengths [Nicholson et al., 1978]. Unfortunately, structures with such a small spatial scale are swept by the spacecraft on a time scale less than 1 msec., which is too small to be resolved by the Helios instrumentation. Therefore no definitive statement can be made concerning the possible occurrence of solitons from the Helios observations. Although the plasma oscillations are very impulsive, it is interesting to note that the peak amplitudes in Figure 2 remain very nearly constant at a level of about 3 to 5 mVm^{-1} for nearly half an hour. Not all events display this flat top characteristic; however it occurs sufficiently often to suggest that the plasma oscillation intensities are being limited by some nonlinear saturation mechanism.

To investigate the variation in the electron plasma oscillation intensities with radial distance from the sun, the maximum electric field strength for each of the ninety events currently available for analysis is shown as a function of heliocentric radial distance in Figure 3. This plot is an update of an earlier report by Gurnett et al. [1978] with a substantial increase in the number of data points, mainly due to the greatly increased solar activity in the last year and one half, as solar maximum approaches. Figure 3 clearly shows that the electric field strength of the plasma oscillations decreases with increasing radial distance from the sun. The best fit power law through all of the data points is shown by the dashed line. The current best estimate for the power law index is -1.4 ± 0.5. This index has changed substantially from the earlier results of Gurnett et al. [1978] as more events have been analyzed. The trend toward decreasing plasma oscillation intensity with increasing radial distance from the sun is consistent with the expected radial variation of the saturation field strength. If the electric field to plasma energy density ratio, $E^2/8\pi nkT$, at saturation is constant, then E should vary approximately as $(1/R)^{1.14}$, since the electron density, n, varies as $(1/R)^2$ and the temperature, T, varies as $(1/R)^{2/7}$ [Hundhausen, 1972]. A representative maximum value for $E^2/8\pi nkT$, shown by the solid line at the top of Figure 3, is about 2×10^{-5}.

COMPARISON WITH TYPE III EMISSIVITIES

To compare the plasma oscillation intensities in Figure 3 with existing theories, it is necessary to determine the typical emissivity of a type III radio burst, particularly in the radial distance range

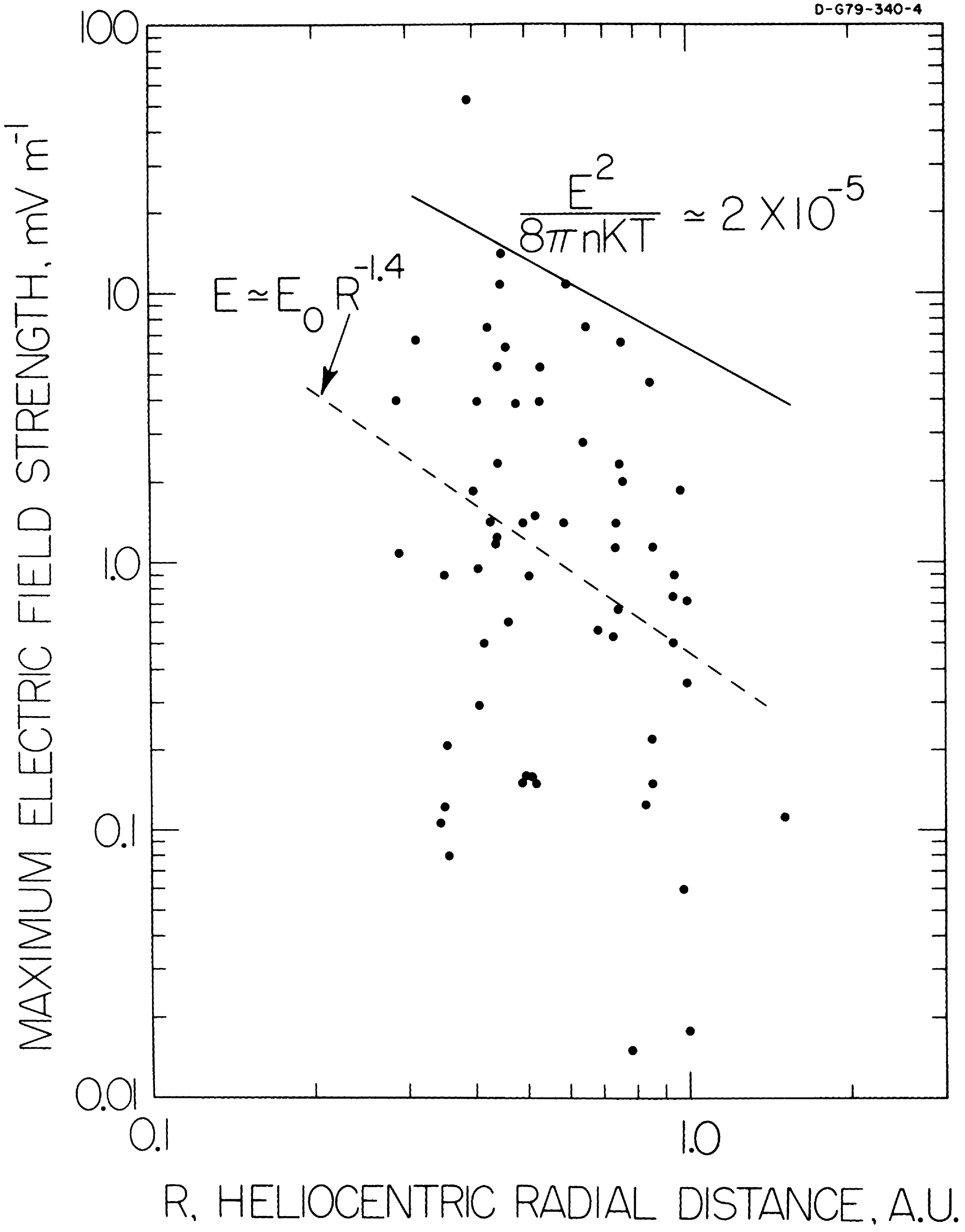

Figure 3. A plot of the peak electric field strength for all of the plasma oscillation events with type III bursts detected to date as a function of radial distance from the sun.

from about 0.3 to 1.0 A.U. where in situ measurements of plasma observations are available. In principle, a comparison of the radial variation of the plasma oscillation intensities and the type III emissivity provides a powerful test, since any given mechanism implies a specific relationship between these two parameters. Recently Tokar and Gurnett [1979] have completed an analysis of the radial variation of the emissivity of low frequency type III radio bursts. The technique used consists of computing the power ΔP emitted in volume ΔV with the emissivity defined as $J(2f_p^-) = \Delta P/4\pi\Delta V$, where it is assumed, for simplicity, that the radiation is emitted isotropically over a solid angle of 4π. The power is computed from $\Delta P = 4\pi r^2 I\Delta f$, where r is the distance from the source to the spacecraft, Δf is the bandwidth and I is the power flux, in watts $m^{-2}Hz^{-1}$, at the spacecraft. The volume is computed from $\Delta V = R^2\Delta R\Omega$, where Ω is the solid angle of the emitting region as viewed from the sun. Since it is usually not possible to directly determine Ω, we have assumed that the source subtends a half-angle of 45.0° as viewed from the sun, which is consistent with the results of Baumback et al. [1976]. The center of the source volume is assumed to follow the magnetic field line through the originating flare location using the magnetic field model of Parker [1958] with a solar wind velocity of 400 km s^{-1}. The emission frequency is assumed to be at the harmonic of plasma frequency, following the radial variation given by Fainberg and Stone [1974]. The results of this analysis, as applied to thirty-six type III radio bursts, are shown in Figure 4. Because of the uncertainty in the solid angle Ω the absolute value of J probably has a substantial uncertainty, perhaps as much as a factor of 2 or 3. This uncertainty is, however, small compared to the variations from event to event. Except for certain special cases, for example when the source passes close to the spacecraft, the radial dependence tends to be rather independent of the assumptions used. In all cases the emissivity decreases monotonically with increasing radial distance from the sun and a power law provides a good fit to the radial variation. The average power law index for all of the events analyzed is -6.0 ± 0.3. The best fit power law through all of the data points is shown by the dashed curve in Figure 4.

Having established the radial dependence and absolute intensity of both the plasma oscillations and the radio emissivity, comparisons can now be made with specific models for the generation of type III radio bursts. Two models will be evaluated, the coherent parametric (oscillating two-stream) mechanism of Papadopoulos et al. [1974], and the incoherent induced scattering mechanism of Smith [1977]. The emissivity given by Papadopoulos et al. [1974], converted to MKS units and evaluating constants (using $\alpha = 0.1$), is

$$J(2f_p^-) = 5.83 \times 10^{-15} \left(\frac{T}{T_o}\right)^{3/2} \frac{E^4}{\sqrt{n}}, \text{ watts } m^{-3}sr^{-1}, \qquad (1)$$

where E is the electric field strength of the plasma oscillations in Volts m^{-1}, n is the electron density in cm^{-3}, T is the electron

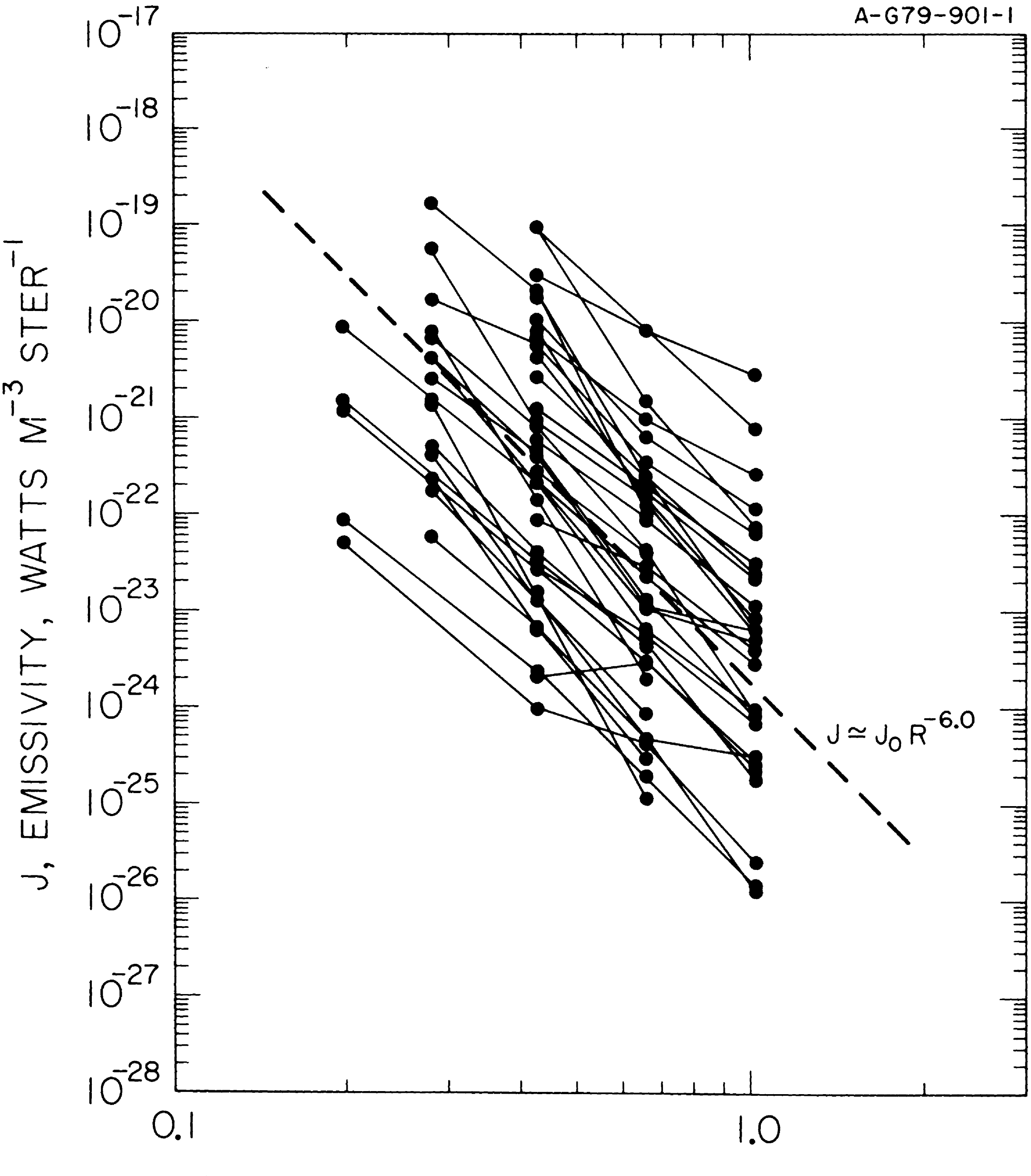

Figure 4. The emissivity as a function of radial distance from the sun determined from thirty-six type III radio bursts detected by IMP 8 and ISEE 1.

temperature in $^{\circ}K$, and T_o is the electron temperature at 1 A.U., $\sim 1.2 \times 10^5$ $^{\circ}K$. The corresponding emissivity given by Smith [1977] is

$$J(2f_p^-) = 1.12 \times 10^{-13} \frac{E^4}{\sqrt{n}}, \text{ watts } m^{-3} sr^{-1}, \qquad (2)$$

where E is again in Volts m^{-1}, and n is in cm^{-3}. Both the coherent and incoherent mechanisms have essentially the same dependence on the electric field strength and electron density, and differ only slightly in the temperature dependence. As can be seen the dominant dependence, by far, is on the electric field strength of the plasma oscillations. Since the electron density and temperature in the solar wind vary as $n \sim (1/R)^2$ and $T \sim (1/R)^{2/7}$, and since J varies as $(1/R)^{6.0 \pm 0.3}$, the expected radial variation of E from Equation 1 for the model of Papadopoulos et al. [1974] should be $(1/R)^{1.64 \pm 0.1}$. For the model of Smith [1977] the corresponding radial variation of E from Equation 2 should be $(1/R)^{1.75 \pm 0.1}$. Both of these predictions compare very favorably with the observed radial variation for E of $(1/R)^{1.4 \pm 0.5}$.

In addition to comparing the radial variations with the theoretical predictions the absolute values of the emissivity can also be compared. From Figure 3 it is seen that the largest plasma oscillation field strength at 1 A.U. is about $E \simeq 5$ mVm^{-1}. Using this maximum field strength, the corresponding emissivities given by Papadopoulos et al. [1974], using Equation 1, and Smith [1977], using Equation 2, are 1.63×10^{-24} and 3.13×10^{-23} watts $m^{-3}sr^{-1}$, respectively. Comparing these emissivities with Figure 4 it is seen that the emissivity computed from Smith's model would be able to account for about 85% of all the events observed at 1.0 A.U., whereas Papadopoulos' model would be able to account for only about 30% of the events observed. Thus, it appears that for the largest plasma oscillation intensities observed the incoherent model of Smith [1977] is able to account for the emissivity of all but the most intense radio bursts, whereas the model of Papadopoulos et al. [1974] is not able to account for a burst of average intensity. It should also be pointed out that Smith [1977] has already demonstrated in a specific case that the incoherent mechanism can account for the simultaneously observed radio emission intensities with a substantial margin. The case considered by Smith [1977] was, however, a particularly intense plasma oscillation event, with an intensity (14.8 mVm^{-1}) near the upper limits of the events shown in Fig 3. If instead of taking the most intense plasma oscillation event, one takes more typical intensities representative of, for example, the best fit power law (dashed line) in Figure 3, then the emissivity is drastically reduced because of the E^4 dependence in Equations 1 and 2. For these more typical plasma oscillation intensities, both the models of Papadopoulos et al. [1974] and Smith [1977] give emissivities well below the best fit curve (dashed line) shown in Figure 4. These difficulties are further complicated by the fact that the actual volume of the source is probably substantially smaller than has been assumed in Equations 1 and 2 because of the impulsive variations in the amplitude of the plasma oscillations. In summary it appears that the radial variation of the plasma oscillation intensities and type III emissivity are in good agreement with the current theoretical models but that in all except for the most intense plasma oscillation events the emissivity given by the theory is somewhat smaller than the observed emissivity. Several explanations can be advanced to account for this discrepancy in the absolute emissivity. Probably the most likely possibility is that the plasma oscillations have substantial temporal fluctuations on a time scale short compared to the 50 msec. averaging time of the Helios instrument. If the fluctuations are very impulsive, as seems to be the case, then because of the E^4 dependence of the emissivity the radiation intensity may be substantially underestimated on the basis of the average electric field intensity. Another possibility is that the intense plasma oscillations are confined to very small spatial regions which are very unlikely to be encountered by the spacecraft, thereby tending to bias the electric field intensity measurements, as in Figure 3, more heavily toward lower intensities.

CONCLUSION

These comparisons of plasma oscillation intensities and the emissivity of type III radio bursts show good overall agreement with current theories for the conversion of electron plasma oscillations to electromagnetic radiation at $2f_p^-$. The primary questions remaining involve the fine time scale structure of the plasma oscillations and the relative importance of incoherent and coherent (soliton collapse) processes. Although the absolute emissivities computed in this study tend to favor the incoherent process, it is probably not possible to determine which mechanism is most important because of the uncertainty about the fine time scale variations in the plasma oscillation intensity. Further progress in understanding the possible role of soliton collapse processes in the generation of type III radio emissions will require much higher time resolution measurements than are currently available.

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DISCUSSION

Stewart: Type II bursts show both fundamental and second harmonic structure at kilometric wavelengths. Your observation that the plasma waves are delayed with respect to the radio waves supports, as you say, the hypothesis that fundamentals also occur in type III bursts at kilometric wavelengths, despite what the theorists say.

Gurnett: We can't resolve the fundamental and the second harmonic on the basis of the radio data alone at these frequencies because of the dispersion in time of the emission.

Stewart: Is the radio emission coming from the same place?

Gurnett: Well of course at higher frequencies its coming in closer to the sun and its source is moving out and the situation is that plasma oscillations usually start about the time the radio emission frequency approaches the local plasma frequency. Definitely after the time where it passes the second harmonic.

Stone: Not all information suggesting second harmonic radiation at long wavelengths comes from direction finding. Indeed we can make direct comparisons between the in situ plasma density measurements. We find in all cases looked at thus far that the radio emission is observed at $2f_p$. There is a wealth of other observational data to support the second harmonic radiation. Moreover some isolated cases of fundamental have also been reported.

Gurnett: Let me say that I personally have done direction finding measurements in two spacecrafts that also seem to confirm that emission is coming from the second harmonic. Perhaps in these cases we are right near the source so that we can begin to see the fundamental; its a puzzle I really don't know the answer to this question.

Benz: I have some interest in your observation of ion-acoustic waves since we postulate them in our type I model. What is the energy density of these waves you see in interplanetary space? What do you suggest as their origin?

Gurnett: The plasma energy density is about 10^{-6} to 10^{-7} the electric field energy density or the magnetic field energy density. The question of why they are there is a very puzzling one. There are two theories on this. One is that they are driven by the electron heat flux in the solar wind and of course the real issue is the electron-ion temperature ratio and I have shown that these ion acoustic waves are correlated with the T_e/T_i and tend to occur in regions that have rather high T_e/T_i. The other model is that they are driven by ion streams in the solar wind.