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Electron Plasma Oscillations Associated with Type III Radio Emissions and Solar Electrons

by

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July, 1975

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ABSTRACT

An extensive study of the IMP-6 and IMP-8 plasma and radio wave data has been performed to try to find electron plasma oscillations associated with type III radio noise bursts and low-energy solar electrons. This study shows that electron plasma oscillations are seldom observed in association with solar electron events and type III radio bursts at 1.0 AU. In nearly four years of observations only one event was found in which electron plasma oscillations are clearly associated with solar electrons. For this event the plasma oscillations appeared coincident with the development of a secondary maximum in the electron velocity distribution functions due to solar electrons streaming outwards from the sun. Numerous cases were found in which no electron plasma oscillations with field strengths greater than 1 μV m^{-1} could be detected even though electrons from the solar flare were clearly detected at the spacecraft.

For the one case in which electron plasma oscillations are definitely produced by the electrons ejected by the solar flare the electric field strength is relatively small, only about 100 μV m^{-1}. This field strength is about a factor of ten smaller than the amplitude of electron plasma oscillations generated by electrons streaming into the solar wind from the bow shock. Electromagnetic radiation, believed to be similar to the type III radio emission, is also observed coming from the region of the more intense electron plasma oscillations upstream of the bow shock. Quantitative calculations of the rate of conversion of the plasma oscillation energy to electromagnetic radiation are presented for plasma oscillations excited by both solar electrons and electrons from the bow shock. These calculations show that neither the type III radio emissions nor the radiation from upstream of the bow shock can be adequately explained by a current theory for the coupling of electron plasma oscillations to electromagnetic radiation. Possible ways of resolving these difficulties are discussed.

I. INTRODUCTION

Type III solar radio noise bursts are closely associated with solar flares and are characterized by an emission frequency which decreases with increasing time. Wild [1950] first proposed that type III radio emissions are generated at frequencies near the electron plasma frequency by charged particles moving rapidly outward through the solar corona. The decreasing plasma frequency encountered by these particles as they move away from the sun accounts for the decrease in the emission frequency with increasing time. The frequency range of type III bursts is very large, extending from frequencies of several hundred MHz to frequencies as low as 20 kHz. The low frequency limit for observing a type III burst near the earth is determined by the local solar wind plasma frequency which is typically about 20 kHz. Simultaneous observations of solar radio emissions and charged particles ejected by solar flares [Lin, 1970; Frank and Gurnett, 1972; Alvarez et al., 1972; Lin et al., 1973] have established that type III radio bursts are produced by electrons with energies ranging from a few keV to several tens of keV.

The generation of electromagnetic radiation at or near the electron plasma frequency is generally thought to be a two-step process in which electrostatic plasma oscillations are first produced at the local electron plasma frequency by a two-stream instability and then these plasma oscillations generate electromagnetic radiation by nonlinear interactions. The electron plasma oscillation hypothesis for explaining type III radio emissions was first proposed by Gintsburg and Zheleznyakov [1958] and has been modified and refined by many investigators including Sturrock [1961], Tidman et al. [1966], Kaplan and Tsytovich [1968], Smith and Fung [1971] and Papadopoulos et al. [1974]. According to current ideas nonlinear interactions can transform the electrostatic energy of the plasma oscillations into electromagnetic radiation at either the fundamental (f_p) or harmonic ($2f_p$) of the electron plasma frequency. The radiation at the fundamental is caused by the scattering of electron plasma oscillations from ion density fluctuations, and the radiation at the second harmonic is caused by the scattering of electron plasma oscillations from each other. Radiation at both the fundamental and the harmonic has been detected from type III bursts at high frequencies ~ 100 MHz [Wild et al., 1954]. At lower frequencies, < 1 MHz, direction finding measurements indicate that most of the radiation occurs at the harmonic [Fainberg and Stone, 1973; Kaiser, 1975].

Since type III radio emissions are almost certainly generated at radial distances extending out to and beyond earth it should be possible to directly observe the electron plasma oscillations which are postulated to be associated with a type III radio burst. In an earlier paper [Frank and Gurnett, 1972], a type III radio burst and the associated solar electrons were analyzed in detail. Although the spacecraft was clearly within the solar electron stream ejected by the flare no electron plasma oscillations were observed which could be associated with these electrons. No secondary maximum in the electron velocity distributions, which was attributable to these streaming solar electrons, was found for this previously published example. The purpose of the present paper is to present the results of an extensive search for electron plasma oscillations associated with type III radio noise bursts and to compare type III radio emissions with similar radiation coming from upstream of the bow shock at the harmonic of the local electron plasma frequency.

II. INSTRUMENTATION

The plasma wave and charged particle measurements used in this study were obtained with instrumentation on the IMP-6 (Explorer 43), IMP-7 (Explorer 47) and IMP-8 (Explorer 50) satellites. IMP-6 was launched on March 13, 1971, into a highly eccentric orbit with initial perigee and apogee geocentric radiation distances of 6620 km and 211,250 km, respectively, and an inclination of 28.6°. Data reception for IMP-6 continued from launch until the spacecraft reentered the earth's atmosphere on October 2, 1974. IMP-7 was launched on September 23, 1972, into a low eccentricity orbit with initial perigee and apogee geocentric radial distances of 207,481 km and 241,978 km, respectively, and an orbit inclination of 17.2°. IMP-8 was also injected into a low eccentricity orbit with initial perigee and apogee geocentric radial distances of 147,434 km and 295,054 km, respectively, and an orbit inclination of 28.6° on October 26, 1973. Telemetry from both IMP-7 and IMP-8 is still being received at the present time. These spacecraft all provide long periods of observations in the solar wind upstream of the earth's bow shock.

Each of these three satellites has a Low Energy Proton and Electron Differential Energy Analyzer, or LEPEDEA, which provides measurements of the differential energy spectrums and angular distributions of protons and electrons with high sensitivity. The energy range of each LEPEDEA is 50 eV $\leq$ E $\leq$ 45 keV. Electron and proton energy spectrums are each sampled in 16 energy passbands and in 16 directions (sunsectored) for each passband. The fields-of-view of the LEPEDEA are approximately rectangular, 8° x 30°, and their axes are oriented perpendicular to the satellite spin axes. The spin axes of all three satellites are directed perpendicular to the ecliptic plane. The LEPEDEA also includes a collimated, thin-windowed Geiger-Mueller tube which is sensitive to electrons with energies $E \geq 45$ keV and to protons with energies $E \geq 650$ keV. The field-of-view of the Geiger-Mueller tube is also perpendicular to the satellite spin axis. Further information concerning the LEPEDEA instrumentation has been published previously [Frank, 1967; Frank et al., 1969].

The University of Iowa plasma wave instruments which are included on IMP-6 and IMP-8 are designed to make measurements over a very broad frequency range, 20 Hz to 200 kHz for IMP-6 and 40 Hz to 2.0 MHz for IMP-8, with high sensitivity and large dynamic range. Both experiments employ "long" electric dipole antennas, 92.5 meters tip-to-tip for IMP-6 and 121.5 meters tip-to-tip for IMP-8, which are extended outward perpendicular to the spacecraft spin axes. The signals from these antennas are analyzed by multichannel spectrum analyzers, each channel of which has a bandwidth of approximately ten percent of the center frequency with four filters per decade of frequency. The spectrum analyzer on IMP-6 has sixteen channels from 36 Hz to 178 kHz and the spectrum analyzer on IMP-8 has fifteen channels from 40 Hz to 178 kHz. Further details of these instruments are given by Gurnett [1974].

III. A SURVEY OF EVENTS ANALYZED

The detection of electron plasma oscillations in association with a type III radio noise burst presents several observational problems. Near the earth electron plasma oscillations are generated by ~ 1 keV electrons which escape upstream into the solar wind from the earth's bow shock [Scarf et al., 1971; Fredricks et al., 1971]. Since the electrons from the bow shock are guided along the magnetic field in the solar wind these plasma oscillations only occur on magnetic field lines which intersect the bow shock. Because these upstream plasma oscillations are observationally indistinguishable from plasma oscillations excited by electrons of solar origin it is impossible to identify plasma oscillations associated with a type III burst if the upstream plasma oscillations are present. Because the region affected by the electrons from the bow shock is so large the chance of observing plasma oscillations associated with a type III burst is quite small for an earth-orbiting satellite. Even when there is no apparent contamination from bow shock electrons considerable care must be exercised to make certain that a burst of plasma oscillations which has the expected temporal relationship with a type III burst is not caused by a sporadic burst of electrons from the bow shock. The only way to definitely eliminate bow shock electrons from consideration is by measurements of the electron angular distributions to confirm that no electrons are reaching the spacecraft from the bow shock.

To perform this study a total of 87 type III radio noise bursts was analyzed. These events comprise all the type III events detected by IMP-6 and IMP-8 in the solar wind over a 46 month period extending from April 1, 1971, to February 2, 1975. Based on the frequency drift rate of the type III burst the expected onset time of the plasma oscillations was estimated for each event and the frequency channels near the local electron plasma frequency were inspected for enhanced electric field amplitudes. For many of the events studied electron plasma oscillations produced by electrons from the bow shock made it impossible to identify plasma oscillations associated with the type III event. In other cases the heliographic longitude of the solar flare producing the type III event was such that the solar electrons did not pass sufficiently close to the earth to be detected. Of the 87 events studied only one case, which is discussed in the next section, was found for which plasma oscillations were associated with electrons of solar origin. However, at least 8 events were found in which no plasma oscillations were detected even though electrons from the solar flare were clearly evident in the LEPEDEA and the Geiger-Mueller tube responses. One such case is the event of April 6, 1971, discussed by Frank and Gurnett [1972].

This survey of type III events detected by IMP-6 and IMP-8 shows that it is very difficult to find electron plasma oscillations associated with a type III radio noise burst. Although the number of cases in which a definitive determination can be made was severely limited by the contaminating effect of electrons from the bow shock it appears that in most cases plasma oscillations are <u>not</u> detected in association with a solar electron event detected near the earth. The electric field sensitivity for detecting these plasma oscillations is about 1 $\mu V\ m^{-1}$, or less.

IV. A SOLAR ELECTRON EVENT WITH PLASMA OSCILLATIONS

The only event found in the IMP-6 and IMP-8 observations, for which electron plasma oscillations can be definitely associated with a solar electron event and a type III radio burst, is illustrated in Figure 1. The solar flare which produced this event was detected on the ground by both optical and high frequency radio measurements and started at 1530 UT on November 5, 1974 [NOAA, 1974]. The flare region is located at S12° and W76° and is in a favored position for the ejected electrons to reach the earth along the Archimedean spiral of the interplanetary magnetic field. The type III radio burst produced by this flare is first detected by IMP-8 at 1535 UT in the 500 kHz frequency channel. The radio emission is subsequently detected in the 178 kHz, 100 kHz and 56.2 kHz channels, shown in the middle panels of Figure 1, with a progressively increasing time delay typical of a type III radio burst. This type III burst is very intense, particularly at high frequencies, and saturates the receiver for a short period from about 1535 to 1540. The interval during which the receiver is saturated is indicated by dashed lines in Figure 1.

The energetic electrons ejected by the flare are first detected by the Geiger-Mueller tube on IMP-8 at about 1550 UT. The electron directional intensities with $E > 45$ keV and arriving from directions near that of the sun, $22° \leq \phi^{L}_{SE} \leq 338°$, are shown in the top panel of Figure 1. The angular coordinate ϕ_{SE}^{L} is the spacecraft-centered solar ecliptic longitude of the LEPEDEA field-of-view. The solar wind magnetic field direction during the event remains within a few degrees of $\phi_{SE} = 0°$ and the highest electron intensities also occur when the instrument field-of-view is directed close to the sun. These electron ($E > 45$ keV) intensities increase rapidly and reach a nearly constant plateau intensity of about 2×10^3 electrons $(cm^2\text{-sec-sr})^{-1}$ by about 1630 UT.

Lower energy electrons ejected by the flare are also detected by the LEPEDEA with longer time delays at lower energies. As an example, differential, directional intensities of electrons at 7.7 keV and $11° \leq \phi_{SE}^{L} \leq 349°$, i.e., travelling in nearly antisolar directions, are shown in the second panel of Figure 1. The arrival time of the 7.7 keV electrons is about 1630 UT which is in good agreement with the expected arrival time at this energy. The intensities of these electrons fluctuate considerably and gradually increases to a plateau intensity of about 15 electrons $(cm^2\text{-sec-sr-eV})^{-1}$ over a period of about 1 hour.

Simultaneous electric field measurements near the local electron plasma frequency reveal several intense bursts of noise in the 31.1 kHz frequency channel during this event, as shown in the second panel from the bottom in Figure 1. The bandwidth of these bursts is very narrow and the abrupt temporal variations are characteristic of the electron plasma oscillations frequently observed upstream of the bow shock. The frequency of these bursts is consistent with the electron plasma frequency determined from the Los Alamos solar plasma instrument on IMP-8 [personal correspondence,

M. Montgomery, 1975]. During the interval from 1500 to 1900 UT, the electron density is nearly constant at approximately 16 electrons cm^{-3}, which corresponds to an electron plasma frequency of 36.0 kHz. Because of the close agreement between the frequency of the bursts and the electron plasma frequency obtained from the local density measurement these bursts are almost certainly electron plasma oscillations. To determine if these plasma oscillations are produced by electrons from the bow shock the electric field intensities at 31.1 kHz are compared in Figure 2 with the electron intensities at E = 1.2 keV arriving from the direction of the bow shock, $102° \leq \phi_{SE}^{L} \leq 258°$. An energy of 1.2 keV is typical for electrons from the bow shock. It is evident from Figure 2 that the plasma oscillation bursts at 1515 UT, 1525 UT, 1612 UT and 1845 UT are clearly associated with intense bursts of 1.2-keV electrons arriving from the bow shock. For the period from 1625 UT to 1730 UT electron plasma oscillations are still present even though no electrons can be detected from the bow shock. As will be shown these electron plasma oscillations are produced by low-energy electrons arriving from the sun.

The origin of the plasma oscillations observed during this event is most clearly illustrated by the electron energy spectrums in Figures 3 and 4. Figure 3 shows the energy spectrum of electrons arriving from the bow shock, $102° \leq \phi_{SE}^{L} \leq 258°$, at three times, 1558 UT, 1614 UT and 1641 UT, indicated by the vertical dashed lines in Figure 2. The general increase in electron intensities toward lower energies is attributed to the quiescent solar wind electron distribution, more specifically, the 'halo' component [cf. Feldman et al., 1975]. At 1558 UT, when no plasma oscillations are observed, the electron spectrum shows a slight peak at about 600 eV, probably produced by electrons from the bow shock. When the intensity spectrum, dJ/dE, is converted to a velocity distribution function, $f(v)$, the peak at 600 eV disappears because of the change in slope caused by the $(1/v)^2$ factor in the transformation

$$f(v) = \frac{m}{v^2}\left(\frac{dJ}{dE}\right) .$$

According to the Penrose [1960] criterion the plasma at 1558 UT is therefore stable, thereby accounting for the absence of electron plasma oscillations at this time. At 1614 UT, when intense plasma oscillations are present, the electron spectrum has a very pronounced peak at 600 eV. This maximum, together with the maximum associated with the ambient solar wind spectrum at $E < 100$ eV, produces a clearly defined double peak in the velocity distribution function. It is well known that this type of distribution function is unstable for electrostatic waves with phase velocities in the region of positive slope, $\partial f/\partial v > 0$, between the two peaks. The secondary maximum in the distribution function caused by electrons from the bow shock therefore accounts for the presence of intense electron plasma oscillations at this time. At 1641 UT, when moderately intense electron plasma oscillations are present, no secondary maximum is evident in the spectrum of electrons arriving from the direction of the bow shock. Since the spectrum must have two maxima for instability to occur the plasma oscillations which are present at this time cannot be caused by electrons from the bow shock.

Figure 4 shows the energy spectrums of electrons arriving from the direction of the sun at three times selected to illustrate the role of the solar electrons in generating plasma oscillations during this event. Observations are shown from both the IMP-7 and IMP-8 satellites, which are located 79.7 R_e apart at the time these spectrums were obtained, to show that similar spectrums are observed at widely separated positions in the solar wind. The geocentric solar ecliptic longitude, latitude and radial distance of IMP-7 are $\phi_{SE} = 19°$, $\theta_{SE} = 28°$ and $R = 39.2\ R_e$. The corresponding coordinates of IMP-8 are $\phi_{SE} = 229°$, $\theta_{SE} = -41°$ and $R = 42.8\ R_e$.

The first set of spectrums in Figure 4, from 1606 UT to 1613 UT for IMP-8 and from 1610 UT to 1617 UT for IMP-7, corresponds to a period when intense plasma oscillations are being generated by electrons from the bow shock (compare with 1614 UT in Figures 2 and 3). Although possibly some flare-associated energetic solar electrons are being detected at this time, the energy spectrum of the electrons arriving from the sun has not yet developed a secondary maximum large enough to trigger an instability. The electron plasma oscillations present at this time must, therefore, be attributed entirely to the electron intensities arriving from the bow shock. The second set of spectrums in Figure 4, from 1639 UT to 1646 UT, corresponds to the period when moderately intense plasma oscillations are present, but for which there are no electrons arriving from the bow shock (compare with 1641 UT in Figures 2 and 3). The energy spectrum of the electrons arriving from the sun at this time exhibits a pronounced secondary maximum at an energy of about 7.7 keV. The presence of this peak confirms that the plasma oscillations observed during the period from about 1625 UT to 1730 UT are being generated by solar electrons. The simultaneous measurements by both IMP-7 and IMP-8 at widely separated locations in the solar wind show that this peak is not caused by some small local disturbance. The third set of spectrums in Figure 4, from 1714 UT to 1721 UT, corresponds to a period when no plasma oscillations are being observed. By this time the second maximum produced by the solar electrons has completely disappeared, thereby accounting for the absence of plasma oscillations.

The sequence of energy spectrums shown in Figures 3 and 4 provides a detailed confirmation of the origin of the plasma oscillations observed during this event. The bursts of plasma oscillations at 1515 UT, 1525 UT, 1612 UT and 1845 UT are all directly associated with a secondary maximum in the velocity distribution function caused by electrons arriving from the bow shock. The energy of these electrons varies considerably from burst to burst and within a given burst, from several hundred eV to a few keV. The generally poor correspondence between the duration of a plasma oscillation burst and the duration of the corresponding electron burst, evident in Figure 2, is caused by this variability in the characteristic energy. The nearly steady level of plasma oscillations from 1625 UT to 1700 UT, and the three shorter bursts from 1700 UT to 1730 UT, are directly associated with the peak in the velocity distribution function caused by electrons arriving from the solar flare. The electron energy of the secondary maximum attributed to the solar electrons, ~ 7 keV, is substantially larger than that caused by the bow shock electrons, ~ 600 eV. Because of this difference in the characteristic electron energies and the steep spectrum of the ambient solar wind electrons the intensity of the peak required to produce plasma oscillations is substantially less for the solar electrons, $dJ/dE \simeq 10^{2}$ electrons $(cm^2\text{-sec-sr-eV})^{-1}$, than for the bow shock electrons, $dJ/dE \simeq 10^{4}$ electrons $(cm^2\text{-sec-sr-eV})^{-1}$. From the velocity at which the region of positive slope occurs in the distribution function the phase velocity and wavelength of the plasma oscillations can be estimated. For the examples analyzed the wavelengths are $\lambda \simeq 467$ m and $\lambda \simeq 1609$ m for the plasma oscillations associated with the bow shock and solar electrons, respectively. These wavelengths are substantially longer than the length of the electric antennas, a basic requirement for proper determination of the electric field amplitudes. Comparison of the electric field intensities in Figure 2 indicates that the electric field amplitude of the plasma oscillation generated by the solar electrons, ~ 100 μV m^{-1}, is about a factor of ten smaller than the amplitude of the plasma oscillations generated by the bow shock electrons, ~ 1 mV m^{-1}.

V. ELECTROMAGNETIC RADIATION FROM PLASMA OSCILLATIONS UPSTREAM OF THE BOW SHOCK

Recently electromagnetic radiation has been detected coming from the region upstream of the bow shock at the fundamental, f_p, and harmonic, $2f_p$, of the local plasma frequency [Dunckel, 1974; Gurnett, 1975]. Because this radiation appears to be generated by the same basic mechanism as the type III radio emissions the primary characteristics of this noise are described to provide a basis for a quantitative discussion of the generation mechanism.

A typical spectrum of the electromagnetic radiation emitted from the region upstream of the bow shock is shown in the bottom panel of Figure 5. This spectrum was obtained from the IMP-8 spacecraft at a geocentric radial distance of $R = 43.4\ R_e$ and solar ecliptic longitudes and latitudes of $\phi_{SE} = 85.5°$ and $\theta_{SE} = -35.5°$, respectively. Two distinct peaks are evident in the spectrum. The smaller peak is at the local plasma frequency, f_p. The plasma frequency was determined from sporadic bursts of plasma oscillations which occurred both before and after, but not during, the time the spectrum in Figure 5 was obtained. The larger peak is at the harmonic, $2f_p$, of the local plasma frequency. In this case the spectrum remained essentially constant for a period of several hours except for a few brief periods when intense electron plasma oscillations occur at $f \simeq f_p$.

Electromagnetic radiation qualitatively similar to the spectrum shown in Figure 5 is frequently detected for long periods by IMP-8, usually as the spacecraft passes through the region upstream of the bow shock. This radiation is usually very weak, with power levels only slightly above the receiver noise level, and is sometimes difficult to distinguish from continuum radiation coming from the earth's outer radiation zone [see discussion by Gurnett, 1975]. The maximum intensity of this radiation usually occurs at the harmonic, $2f_p$, of the local plasma frequency. In many cases little or no radiation is detected at the fundamental. The intensity is usually constant for periods of hours or more, although sometimes the radiation appears or disappears abruptly. These abrupt changes in the intensity are usually associated with abrupt changes in the direction of the magnetic field in the solar wind. The intensity at $2f_p$ is usually not strongly affected by the occurrence of local electron plasma oscillations, indicating that if the radiation is produced by plasma oscillations then most of the radiation comes from remote locations.

Direction finding measurements with IMP-8 clearly show that the $2f_p$ radiation is generated near and upstream of the earth's bow shock [Gurnett, 1975]. The top panel of Figure 5 shows a series of direction finding measurements of the $2f_p$ radiation at 56.2 kHz for various locations around the earth. It is apparent from these direction finding measurements that most of the ray paths appear to come from the region near and upstream of the bow shock. Measurements of the spin modulation of the received signal strength indicate that the angular size of the source, as viewed by IMP-8 at radial distances of $R \simeq 30\ R_e$, is very large, typically 20° half-angle, or more. Since intense electron plasma oscillations are present throughout the region upstream of the bow shock, and since the primary radiation occurs at the harmonic of the local plasma frequency, it seems very likely that this radiation is produced by nonlinear interactions with the electron plasma oscillations, essentially the same mechanism proposed to explain type III radio bursts.

VI. DISCUSSION

This study shows that electron plasma oscillations are seldom observed in association with solar electron events and type III radio bursts at 1.0 AU. In nearly four years of observations with the IMP-6 and IMP-8 satellites only one event was found in which electron plasma oscillations are clearly associated with solar electrons. This low frequency of occurrence is perhaps to a great extent caused by the considerable difficulty in distinguishing these plasma oscillations from plasma oscillations generated by electrons from the bow shock. Nevertheless, a substantial number of events (8) were found in which no plasma oscillations of any type are detected even though electrons from the solar flare are clearly evident in the LEPEDEA and Geiger-Mueller tube responses. For the case in which electron plasma oscillations were observed the plasma oscillations are clearly associated with a secondary maximum in the electron velocity distribution function, which was produced by solar-flare electrons streaming out from the sun. Similar observations were also shown for electron plasma oscillations excited by electrons from the earth's bow shock. These measurements confirm that electron plasma oscillations are generated in the solar wind by the electrons responsible for type III radio bursts, as first proposed by Gintsburg and Zheleshyakov [1958].

Despite this confirmation several serious difficulties are still present in the plasma oscillation model of type III radio bursts. If type III radio bursts are generated by electron plasma oscillations then the first major difficulty is to explain why plasma oscillations are detected so infrequently relative to the number of solar electron events detected at 1.0 AU. Apparently the only way to resolve this difficulty is to assume that the plasma oscillations are limited to certain small volumes in the solar wind, the total volume of which constitutes a small fraction of the volume exposed to the electron stream ejected by the flare. Direction finding measurements show that the type III radiation cannot be coming from a single small region or flux tube since the angular size of the source becomes very large, $\sim 2\pi$ steradians, at low frequencies [Fainberg and Stone, 1973]. Many small source regions, extending over a large range of solar longitudes and latitudes, are required to explain both the infrequent occurrences of plasma oscillations and the large size of the source. At the present time it is not known what parameters would limit the plasma oscillations to only certain regions in the solar wind. It may be that the plasma oscillations are only marginly unstable and small spatial variations in the ejected electron intensities or solar wind temperature could trigger the instability in certain regions, and quench the instability in other regions. This type of patchy spatial distribution is almost certainly present in the plasma oscillations generated by electrons streaming into the solar wind from the bow shock, as indicated by the highly sporadic amplitude variations usually observed for these waves.

The second major difficulty with the plasma oscillation model of type III bursts is the amplitude of the plasma oscillations. For the November 5, 1974, event the peak electric field strength in the 31.1 kHz channel is about 100 μV m^{-1}. The basic parameter which determines the rate of conversion of the electron plasma oscillation energy to electromagnetic radiation at $2f_p$ is the ratio of the electrostatic energy density of the plasma oscillations, W, to the energy density of the thermal electrons, nkT (where n is the electron number density, k is the Boltzmann's constant, and T is the electron temperature). For the electric field amplitude observed during the November 5 event the electrostatic energy density is $W \simeq 3 \times 10^{-7}$ eV cm^{-3}. Using the solar wind electron density of $n = 10$ cm^{-3} and temperature of 100 eV the corresponding energy density ratio is $W/nkT \simeq 3 \times 10^{-10}$.

To illustrate the radio emission intensity which can be produced by plasma oscillations of this intensity we use the recent theory of Papadopoulos et al. [1974]. According to Papadopoulos et al. the volume emissivity, J, produced by the scattering of electron plasma oscillation at frequency f_p into electromagnetic radiation at $2f_p$ is given by

$$J(\omega \simeq 2\omega_p) = \frac{3\pi^3}{\alpha}\left(\frac{v}{c}\right)^5 \left(\frac{W}{nkT}\right)^2 (nkT)\omega_p \ , \qquad (1)$$

where α is the ratio of the wave-number of the plasma oscillations, k_m, to the Debye wave number, k_D, v is the electron thermal speed and c is the speed of light. The volume emissivity, which has units of power $(\text{volume-steradian})^{-1}$, varies as the square of the energy density ratio, W/nkT, or correspondingly, as the fourth power of the electric field amplitude. To compute the expected power flux of the type III radio emission for our present event we assume that all of the radiation detected in a frequency interval Δf is generated uniformly in a spherical shell of radius R and thickness ΔR centered on the sun. The Poynting vector S just outside of this shell is given by

$$S(4\pi R^2) = V_{rad}\, J\Omega \ ,$$

where V_{rad} is the volume of the radiating region. The solid angle of the emitted radiation, Ω, is assumed to be $\sim 4\pi$. Using $\Delta R/R = \Delta f/f$ for the expected radial variation of the emission frequency the volume of the radiating region is given by

$$V_{rad} = 4\pi R^2\ \Delta f = 4\pi R^3\ (\frac{\Delta f}{f}) \ .$$

Combining these equations the power flux, $p = S/\Delta f$, just outside of the radiating shell at radius R is

$$p = \frac{24\pi^5}{\alpha} R(\frac{v}{c})^5\ (\frac{W}{nkT})^2\ (nkT) \ . \qquad (2)$$

Using $\alpha = 0.1$, $n = 10\ cm^{-3}$, an electron temperature of 100 eV and the observed energy density ratio $W/nkT \simeq 3 \times 10^{-10}$ the computed power flux at $R = 1.0$ AU is $p = 5 \times 10^{-23}$ watts $m^{-2}\ Hz^{-1}$. The observed power flux at $2f_p \simeq 56.2$ kHz for this event is 2.75×10^{-17} watts m^{-2} Hz^{-1}. The observed power flux is therefore about five and one-half orders of magnitude greater than the power flux computed from the theory. Since this calculation assumes a uniform source, which according the our earlier discussion does not agree with the observations, the discrepancy is even larger, probably six to seven orders of magnitude. To account for the observed power flux requires plasma oscillations with field strengths of at least 5 mV m^{-1}.

Because of this large discrepancy it is of interest to determine if the theory of Papdopoulos et al. [1974] can account for the $2f_p$ radiation from upstream of the bow shock, since there is a strong qualitative indication that this radiation is produced by electron plasma oscillations. If we assume that the angular distribution of the radiation is isotropic then the power flux at a distance R from the source is

$$p = \frac{V_{rad}\ J(4\pi)}{4\pi R^2\ \Delta f} \quad . \tag{3}$$

The volume, V_{rad}, of the radiating region is difficult to estimate accurately since it is not known exactly how far plasma oscillations are produced upstream of the bow shock. However, since direction finding measurements usually indicate that the source region is close to the bow shock it appears that the radiation does not come from very far upstream. This conclusion agrees with our impression that the most intense electron plasma oscillations occur within a few earth radii ($\sim 5\ R_e$) upstream of the bow shock. From the angular size of the source, $\sim 20°$ half-angle as viewed by IMP-8 from approximately 30 R_e upstream of the bow shock, we estimate the cross-section of the source to be about 10 R_e x 10 R_e, so that the volume of the radiating region is about $V_{rad} = (10\ R_e) \times (10\ R_e) \times (5\ R_e)$. To obtain an upper limit for the calculated power flux we assume that the source is distributed uniformly throughout this volume. The average electric field amplitude of the upstream electron plasma oscillations is also somewhat uncertain. A typical electric field amplitude for these plasma oscillations is about 1.0 mV m^{-1}. Occasionally larger electric field amplitudes, up to 10.0 mV m^{-1}, do occur; however, these large amplitudes occur very infrequently and would not be consistent with the assumed volume of the radiating region. For this calculation we assume an electric field strength of 1.0 mV m^{-1}, $n = 10\ cm^{-3}$, an electron temperature of 100 eV, $V_{rad} = (10\ R_e) \times (10\ R_e) \times (5\ R_e)$ and $R = 30\ R_e$. Since the bandwidth of the $2f_p$ radiation is probably very small the bandwidth Δf is assumed to be the bandwidth of the spectrum analyzer, $\Delta f/f = 10.4\%$. Using equations (1) and (3) with $\alpha = 0.1$ the computed power flux is $p = 8.23 \times 10^{-24}$ watts $m^{-2}\ Hz^{-1}$. The power flux at $2f_p$ for the spectrum shown in Figure 5 is about 2.5×10^{-19} watts $m^{-2}\ Hz^{-1}$. The observed power flux is therefore about four and one-half orders of magnitude larger than the power flux given by the theory. If the patchy spatial distribution of the plasma oscillations is considered then the discrepancy between the calculated and observed power flux is even larger, probably five to six orders of magnitude. To account for the observed power flux, electron plasma oscillations with electric field strengths greater than 30 mV m^{-1} are required. Plasma oscillations with such large field strengths are observed too infrequently to account for the typical power flux of the $2f_p$ radiation.

These calculations show that neither the type III radio emissions nor the $2f_p$ radiation from upstream of the bow shock can be adequately explained by a current model for the coupling of electron plasma oscillations to electromagnetic radiation. Several possible explanations for this discrepancy between theory and observations must be considered:

(1.) In the case of type III bursts it is possible that measurements have simply never been obtained in the proper location in the solar electron stream to detect the intense plasma oscillations required by the theory. The strong dependence of the emissivity on the electric field strength of the plasma oscillations predicted by the theory tends to support this explanation since a moderate, factor of 100, increase in the field strength can produce the observed power flux from a region sufficiently small that it is unlikely to be observed. This hypothesis is, however, rather unsatisfying since regions with such large field strengths have not been found, despite a rather extensive search, and such inhomogeneities also require a suitable explanation.

(2.) It is possible that the electric field strength measurements of plasma oscillations are in error by a large factor ($>$ 100) because of uncertainties in the effective length or impedance of the electric antennas. This explanation is considered very unlikely since several experiments with much different antenna lengths and characteristics (IMP-6, IMP-8, HAWKEYE-1, and HELIOS-1), as well as measurements with different antenna lengths on the same spacecraft (IMP-6), all give consistent electric field amplitudes for the upstream plasma oscillations.

(3.) Perhaps both the type III radio bursts and the $2f_p$ radiation from upstream of the bow shock are produced "directly" by the non-thermal electrons and are completely unrelated to the occurrence of electron plasma oscillations. Since there appears to be no way of knowing for certain that the plasma oscillation energy is being converted to electromagnetic radiation this possibility remains open. However, at the present time no mechanism is known for the "direct" generation of electromagnetic radiation from the energetic solar electrons without the intermediate generation of electron plasma oscillations.

(4.) Possibly both types of radiation are generated by coupling with electron plasma oscillations but the theoretical models for the conversion of the plasma oscillation energy to electromagnetic radiation are incorrect, or some other mechanism acts to amplify the radiation before it reaches the spacecraft as suggested by Smith [1970]. The qualitative association of the $2f_p$ radiation upstream of the bow shock with electron plasma oscillations and the observation of plasma oscillations associated with electrons ejected from the solar flare during the type III event of November 5, 1974, event provide strong support for this viewpoint.

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FIGURE CAPTIONS

Figure 1 Comparison of simultaneous measurements of a type III radio noise burst, electron plasma oscillations and low-energy electrons arriving from the sun following the solar flare which started at 1530 UT on November 5, 1974. The electron plasma oscillations associated with the ejected solar electrons appear in the 31.1 kHz channel from about 1625 UT to 1730 UT. The bursts of plasma oscillations at 1515 UT, 1525 UT, 1612 UT and 1845 UT are associated with electrons arriving from the earth's bow shock.

Figure 2 Comparison of the electron plasma oscillations observed during the November 5, 1974, event with the intensities of electrons at E = 1.2 keV arriving from the direction of the bow shock. No electrons are detected from the bow shock during the interval from 1625 UT to 1730 UT, showing that the electron plasma oscillations observed at this time are not caused by electrons from the bow shock.

Figure 3 Electron energy spectrums of electrons arriving from the bow shock at three times, indicated by the vertical dashed lines in Figure 2, selected to illustrate the electron energy spectrum which produced the burst of electron plasma oscillations centered at 1612 UT. The burst of plasma oscillations at this time is clearly associated with the distinct peak in the energy spectrum at 1614 UT.

Figure 4 The energy spectrums for electrons arriving from the direction of the sun at two widely separated locations in the solar wind measured nearly simultaneously with IMP-7 and IMP-8. The distinct peak in the energy spectrum from 1639 UT to 1646 UT confirms that the electron plasma oscillations observed at this time are produced by solar electrons.

Figure 5 Direction finding measurements showing electromagnetic radiation coming from upstream of the bow shock at 56.2 kHz. This frequency is approximately twice the normal electron plasma frequency in the solar wind. The bottom panel displays a typical spectrum of this radiation and the sharp peak in the spectrum at twice the local electron plasma frequency.

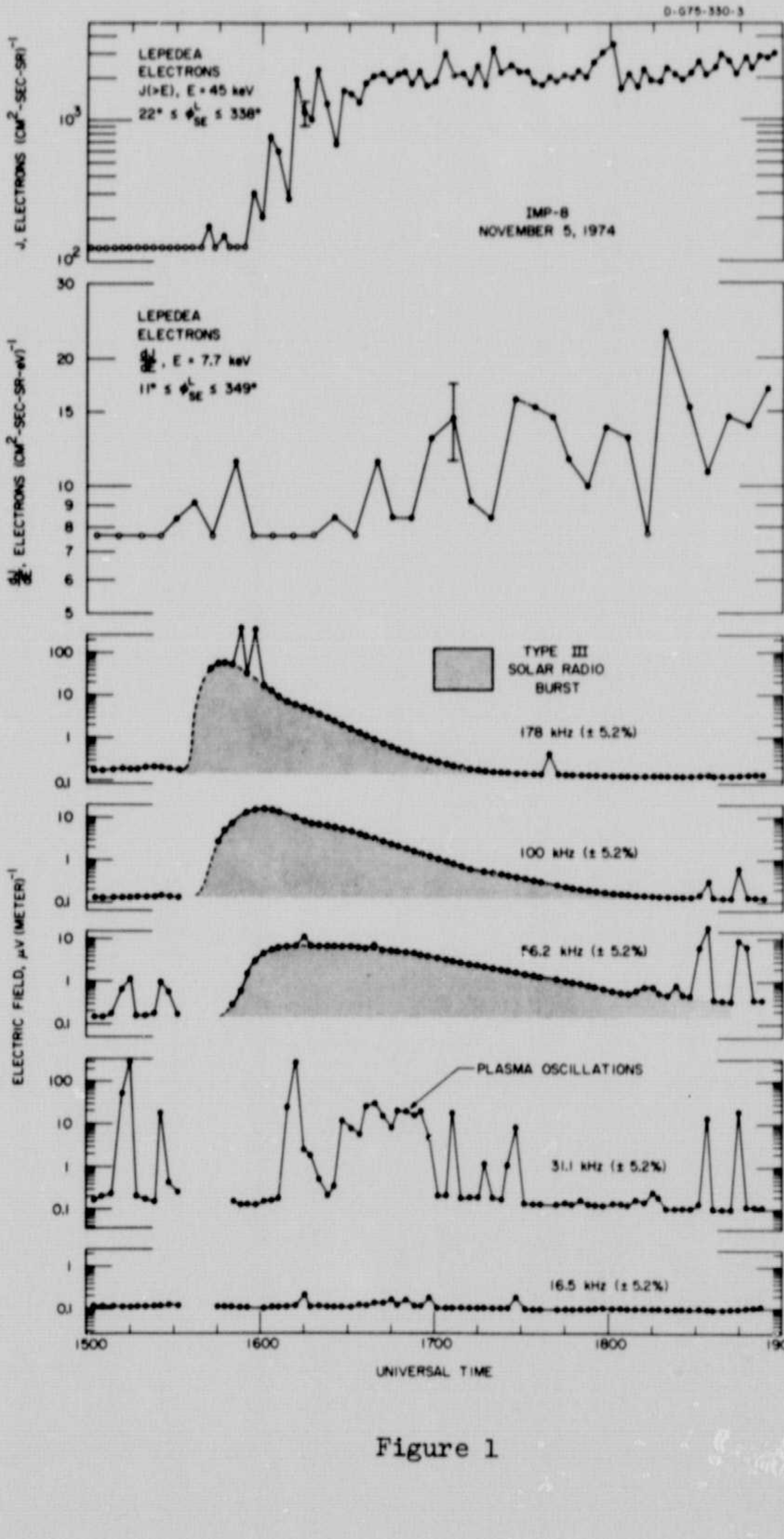
D-G75-330-3
LEPEDEA
ELECTRONS
J(>E), E = 45 keV
22° ≤ ϕ^L_{SE} ≤ 338°
IMP-8
NOVEMBER 5, 1974
J, ELECTRONS (CM²-SEC-SR)⁻¹
LEPEDEA
ELECTRONS
dJ/dE, E = 7.7 keV
11° ≤ ϕ^L_{SE} ≤ 349°
dJ/dE, ELECTRONS (CM²-SEC-SR-eV)⁻¹
TYPE III
SOLAR RADIO
BURST
178 kHz (± 5.2%)
100 kHz (± 5.2%)
56.2 kHz (± 5.2%)
PLASMA OSCILLATIONS
31.1 kHz (± 5.2%)
16.5 kHz (± 5.2%)
ELECTRIC FIELD, μV (METER)⁻¹
1500
1600
1700
1800
1900
UNIVERSAL TIME

Figure 1

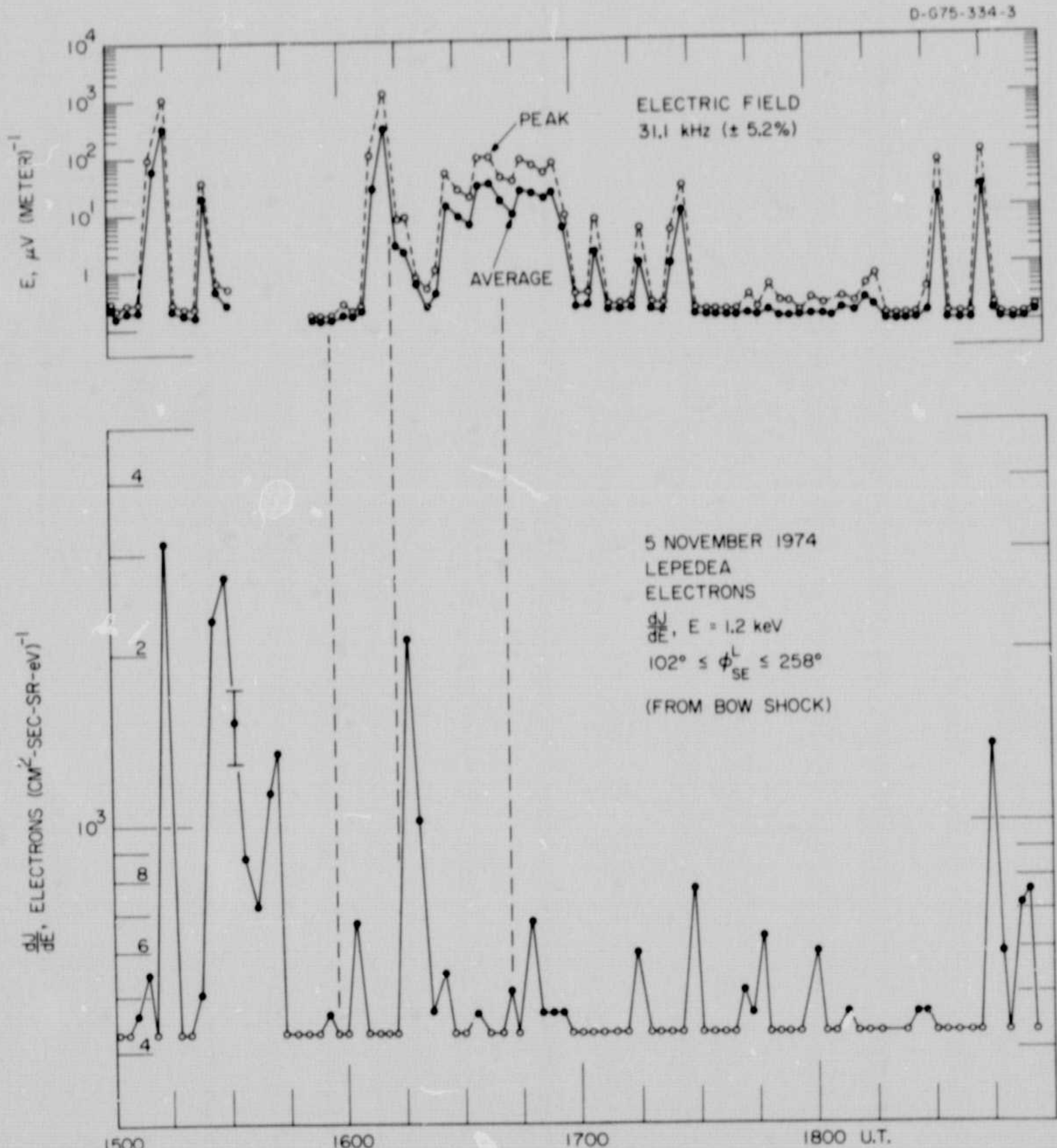

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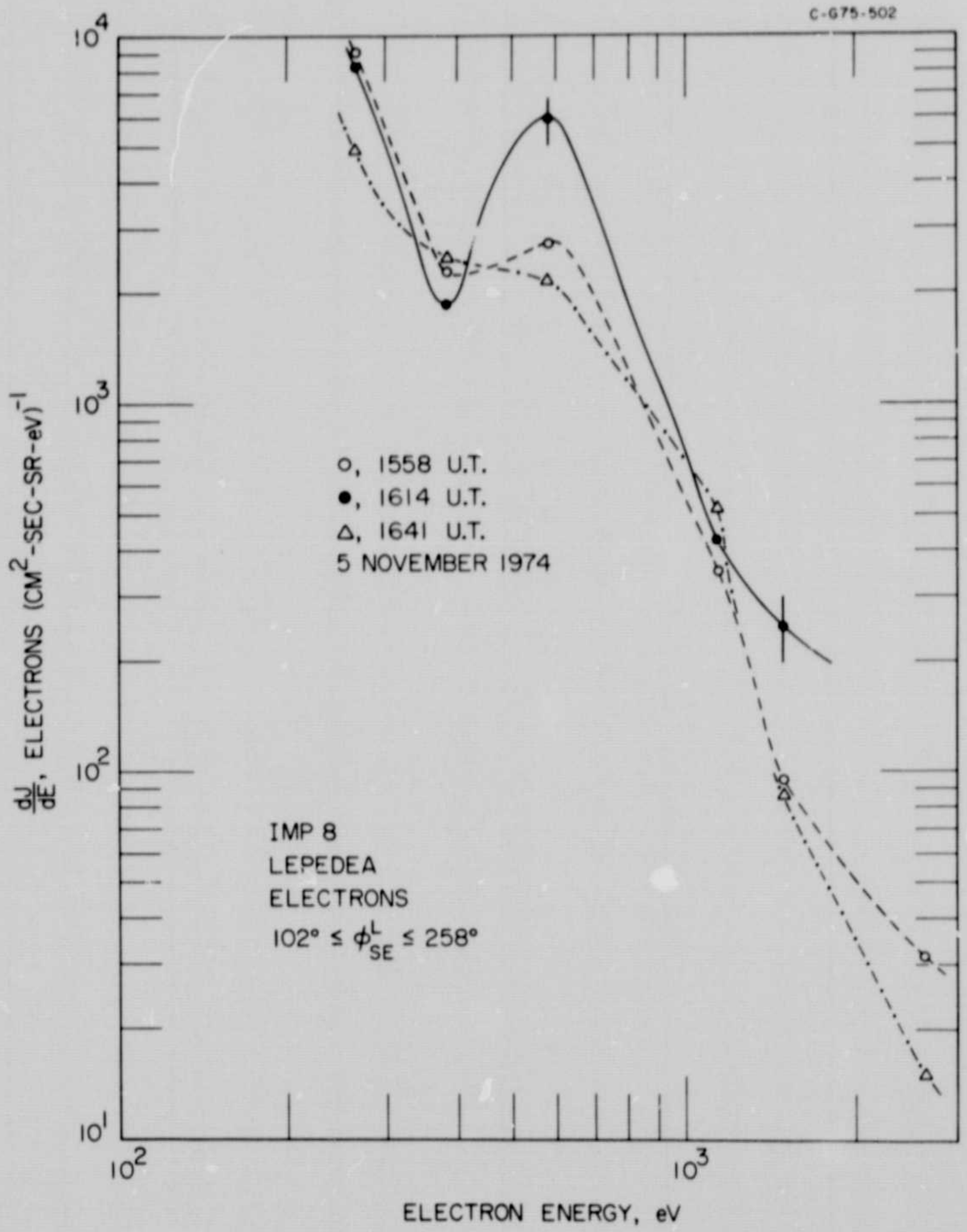
Figure 2



C-G75-502
10^4
10^3
10^2
10^1
10^2
10^3
$\frac{dJ}{dE}$, ELECTRONS $(CM^2\text{-SEC-SR-eV})^{-1}$
ELECTRON ENERGY, eV
○, 1558 U.T.
●, 1614 U.T.
△, 1641 U.T.
5 NOVEMBER 1974
IMP 8
LEPEDEA
ELECTRONS
$102° \leq \phi^L_{SE} \leq 258°$

Figure 3

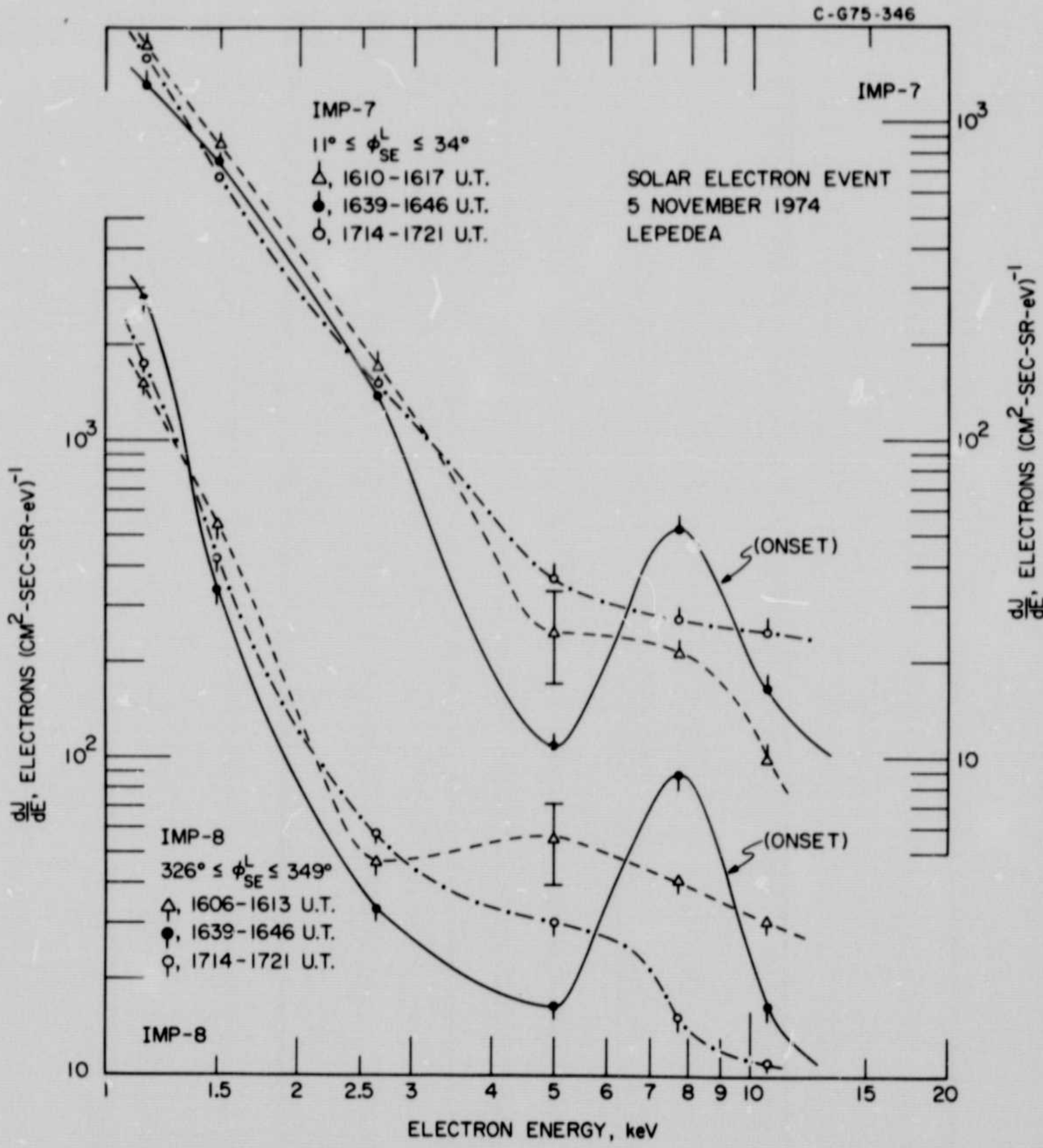
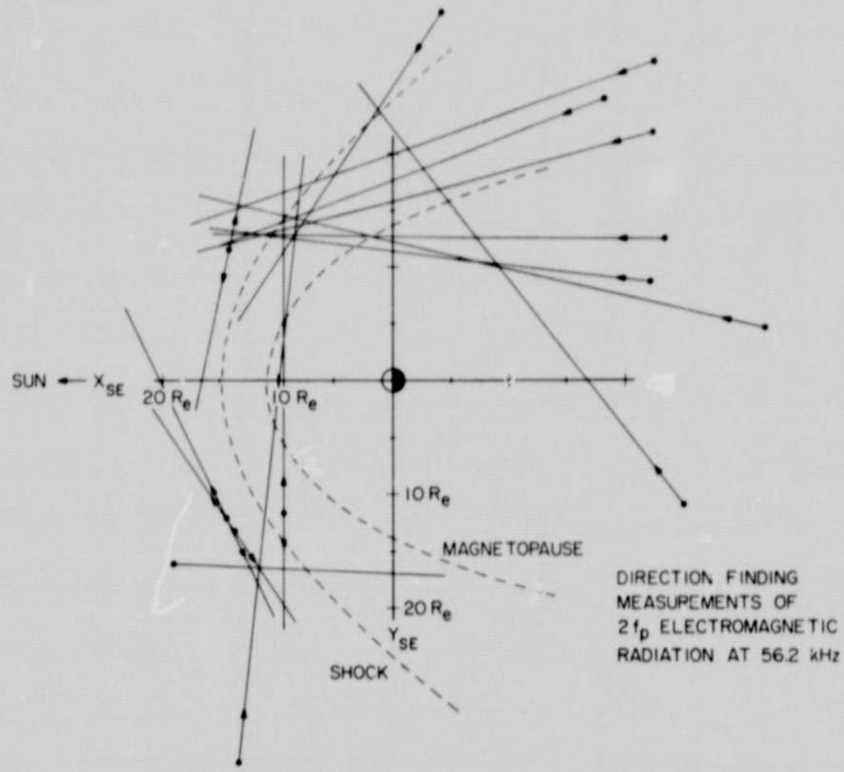

C-G75-346
IMP-7
11° ≤ ϕ^L_{SE} ≤ 34°
△, 1610-1617 U.T.
●, 1639-1646 U.T.
○, 1714-1721 U.T.
SOLAR ELECTRON EVENT
5 NOVEMBER 1974
LEPEDEA
(ONSET)
IMP-8
326° ≤ ϕ^L_{SE} ≤ 349°
△, 1606-1613 U.T.
●, 1639-1646 U.T.
○, 1714-1721 U.T.
(ONSET)
IMP-8
$\frac{dJ}{dE}$, ELECTRONS (CM^2-SEC-SR-eV)$^{-1}$
ELECTRON ENERGY, keV
1
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
10
10^2
10^3

Figure 4

D-G74-903-3



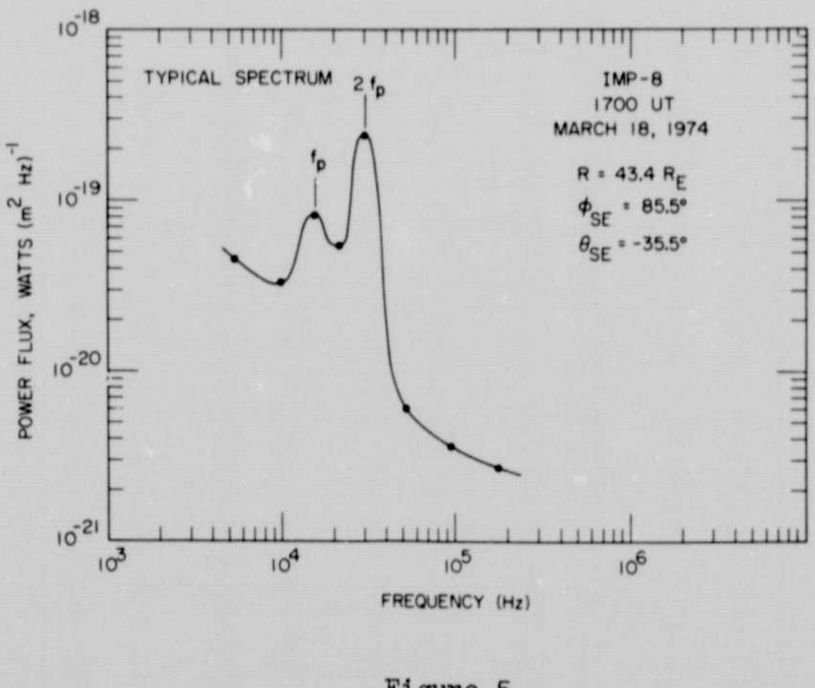


Figure 5