JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 85, NO. A5, PAGES 2353–2356, MAY 1, 1980

# The Volume Emissivity of Type III Radio Bursts

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The volume emissivity has been calculated for thirty-six type III solar radio bursts obtained from approximately 6.5 years of Imp 8 and ISEE 1 satellite data. Although the emissivities for these events vary over a large range, all the emissivities decrease rapidly with increasing heliocentric radial distance. The best fit power law for the emissivity, using the average power law index for all events analyzed, is $J = J_0R^{-6.0}$, with $J_0 = 1.5 \times 10^{-24}$ W m$^{-3}$ sr$^{-1}$. This best fit emissivity is used to estimate the expected radial variation of the plasma oscillations responsible for the type III radio emission.

## INTRODUCTION

Type III solar radio bursts are characterized by an emission frequency which decreases with increasing time. These bursts are produced by solar flare electrons traveling away from the sun along the interplanetary magnetic field lines. The decreasing emission frequency with increasing time is attributed to the decreasing electron plasma frequency encountered by the exciter electrons as they move outward away from the sun [*Wild*, 1950; *Lin*, 1970; *Alvarez et al.*, 1972]. The generation of type III radio bursts is thought to be a two-step process in which electrostatic electron plasma oscillations are first produced by the energetic electron stream and are then converted to electromagnetic radiation by nonlinear interactions [*Ginzburg and Zheleznyakov*, 1958; *Sturrock*, 1961; *Tidman et al.*, 1966; *Papadopoulos et al.*, 1974; *Smith*, 1974]. For a review of low-frequency type III bursts, see, for example, *Fainberg and Stone* [1974]. Plasma oscillations associated with type III bursts are described by *Gurnett and Anderson* [1976, 1977] and *Gurnett et al.* [1978*a*].

The volume emissivity, which is the power emitted per unit volume per unit solid angle, is a fundamental quantity which characterizes all radio emission processes, including type III radio bursts. Because of the recent observations of electron plasma oscillations in association with type III bursts it is now possible to conduct quantitative evaluations of various mechanisms for generating the radio emission. Since little is known concerning the emissivity of type III bursts, particularly in the low-frequency range where direct comparisons with plasma oscillations are possible, it is the purpose of this paper to investigate the emissivity of some representative type III radio bursts. Particular attention will be given to the variation of the emissivity with heliocentric radial distance, since this variation can be directly compared with various generation mechanisms.

The type III events analyzed in this study were obtained from the earth-orbiting Imp 8 and ISEE 1 satellites. The plasma wave instrumentation onboard Imp 8 and ISEE 1 are described by *Gurnett* [1974] and *Gurnett et al.* [1978*c*], respectively.

## METHOD OF CALCULATING THE EMISSIVITY

The emissivity is calculated by using the sun-centered coordinate system shown in Figure 1. The emissivity is defined as

$$J = \frac{\Delta P}{\Delta V \Delta\omega} \text{ W m}^{-3}\text{ sr}^{-1} \qquad (1)$$

where $\Delta P$ is the power radiated in volume $\Delta V$ into a solid angle $\Delta\omega$. Since the angular distribution of the emitted radiation is not known, we will assume that the radiation is emitted isotropically (i.e., $\Delta\omega = 4\pi$). To determine $J$ we measure the spectral power flux at the earth and compute $\Delta P$ using a $1/r^2$ law for the radial variation of the emitted radiation. The isotropy assumption and the simple propagation model used of course introduce an error, since any radiation propagating toward the sun will be reflected, thereby producing an anisotropy in the emitted radiation pattern. The error introduced is, however, at most a factor of 2, which is small in comparison with the wide range of intensities observed from event to event. Also, the isotropy assumption does not affect the radial variation of the emissivity, since sources at all radial distances are treated equivalently.

To compute the power $\Delta P$, the distance from the source to the earth must be determined. Since the source position cannot, in most cases, be determined by direct measurement, a simple model is used for the trajectory of the type III source. The source is assumed to follow the magnetic field in the solar wind starting from the flare location at the sun. The magnetic field model used is that of *Parker* [1958]: in the solar equatorial plane the magnetic field lines are Archimedian spirals, whereas in the meridian plane the field lines stay on a cone of constant heliographic latitude. The heliographic longitude of the associated flare, $\phi_0$, gives the heliographic longitude of the source region, $\phi$, through the Archimedian spiral equation

$$\phi = \phi_0 - (\omega/V_{sw})R \qquad (2)$$

Here $\omega$ is the rotational velocity of the sun, $V_{sw}$ is the solar wind velocity, taken as 400 km/s, and $R$ is the heliocentric radial distance to the source. $R$ is related to the observed emission frequency by using the emission level scale given by *Fainberg and Stone* [1974],

$$f = 66.8R^{-1.315} \text{ MHz} \qquad (3)$$

where $f$ is the observed frequency of the type III burst and $R$ is the heliocentric radial distance in solar radii. The position of the earth above the solar equatorial plane is determined from a simple model for the earth's orbit around the sun.

From the measured radiation intensity $I$ at the time of maximum intensity the power radiated from the source, $\Delta P$, in frequency interval $\Delta f$ is calculated from

$$\Delta P = (4\pi r^2)I\Delta f \qquad (4)$$

Paper number 80A0197.
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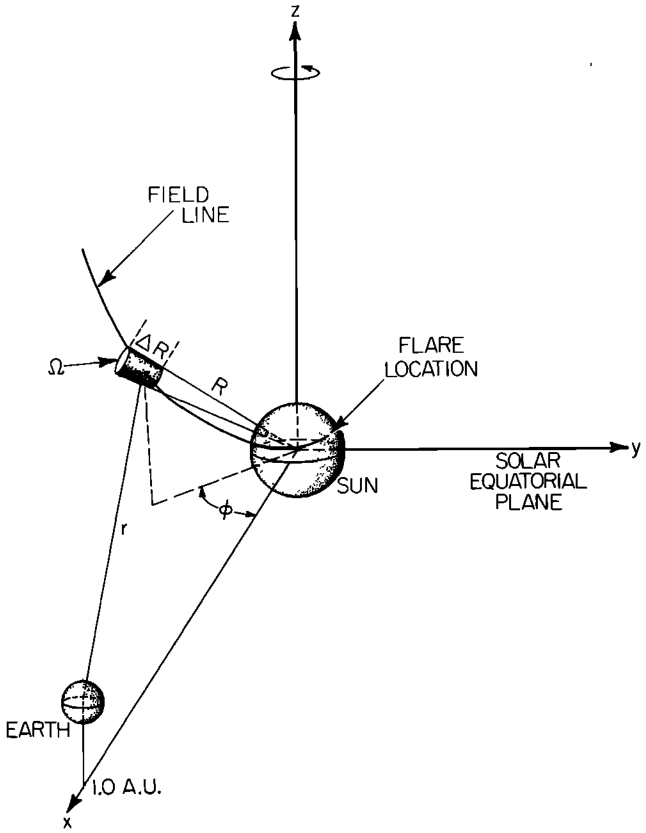

Fig. 1. A perspective drawing showing the geometry used to calculate the emissivity of a type III burst source region. The spectral power flux at the earth gives the power radiated out of the source region and this together with the volume of the source region gives the emissivity.

where $r$ is the radial distance from the source to the earth (see Figure 1). The volume of the source is determined by two factors, the angular size of the source as viewed from the sun, $\Omega$, and the radial thickness $\Delta R$. Since the electrons which produce the radio emission closely follow the interplanetary magnetic field lines, the angular size of the source as viewed from the sun is essentially constant, independent of radial distance from the sun. Since it is often not possible to determine the source size because of geometric considerations, we have assumed a half angle for the source of 45° as viewed from the sun. The corresponding solid angle is $\Omega = 1.84$ sr. This source size is comparable to the source sizes measured by *Baumback et al.* [1976] and *Gurnett et al.* [1978*b*] and is considered a reasonable estimate, since both radio and charged particle measurements indicate that the source must be quite large. The relation of the radial thickness $\Delta R$ to the frequency interval $\Delta f$ can be determined from (3), which gives $\Delta R/R = 1.315\ (\Delta f/f)$. By combining all of these factors the volume of the source becomes

$$\Delta V = \Omega R^2 \Delta R = 1.315 \Omega R^3 (\Delta f/f) \qquad (5)$$

and the emissivity is given by

$$J = (r^2 f/1.315 \Omega R^3) I \qquad (6)$$

Since the emissivity is determined by using average values for the solar wind parameters and since significant deviations from the average parameters may occur in specific cases, the approach taken is to analyze a large number of events and compute an average best fit emissivity, thereby hopefully averaging out the variations which may be present in individual cases. Although the absolute emissivity is probably uncertain by about a factor of 2, mainly due to the difficulty in estimating the angular size of the source, the radial dependence of the emissivity is much more accurately determined, since most of the parameters assumed are nearly independent of radial distance.

## RESULTS AND DISCUSSION

Approximately 5 years of Imp 8 data and 1.5 years of ISEE 1 data were surveyed for type III bursts suitable for analyzing the emissivity. While type III bursts were frequently observed, two main factors limited the number of events used in this study: (1) clear burst maximums needed to be observed in at least three channels in order to give a reasonably accurate indication of the radial variation of the emissivity; and (2) for each event an associated solar flare had to be found in order to determine the trajectory of the source. Of a total of 117 events which showed clear burst maxima, 54 had associated solar flares. Of these, 13 events were common to both satellites. Restricting the study to heliocentric distances less than 1.0 AU eliminated 3 events, while 2 events were eliminated as being inconsistent. Consequently, 36 events were suitable for analysis. Table 1 contains the date, onset time, and flare coordinates for each event.

For each event the emissivity $J$ was calculated as a function of the heliocentric radial distance $R$ and fit to a power law of the form $J = J_0 R^\alpha$. In most cases a power law provided a good least squares fit to the radial dependence, although in a few cases a substantial deviation from a power law was observed. In all cases the power law index $\alpha$ was negative, indicating a decreasing emissivity with increasing radial distance from the sun. Consult Table 1 for the derived $J_0$ and $\alpha$ values. The distribution of the power law indices obtained is shown by the histogram of Figure 2. The highest frequency of occurrence of an $\alpha$ falls in the interval from −4.0 to −6.0, and the average value of all the indices measured is $\bar{\alpha} = -6.0 \pm 0.3$. The standard deviation of the sample is 1.9. Figure 3 shows a composite summary of the emissivity for all the events analyzed. Points common to the same event are connected by a line. As can be seen, the emissivity varies over a large range from event to event. The dashed line shows the best fit of log $J$ to log $J_0 R^{-6.0}$. The best fit value for $J_0$ is $1.5 \times 10^{-24}$ W m$^{-3}$ sr$^{-1}$.

It is clear from these results that the emissivity of low-frequency type III radio bursts decreases very rapidly with increasing radial distance from the sun, with an average power law index of about −6.0. This decrease in the emissivity must be related to a corresponding decrease in the plasma oscillation intensity with increasing radial distance from the sun. From the currently available evidence on type III radio bursts the dominant emission at low frequencies is thought to be at the harmonic, $2f_p^-$, of the local electron plasma frequency [*Fainberg et al.*, 1972; *Haddock and Alvarez*, 1973; *Kaiser*, 1975; *Gurnett et al.*, 1978*b*]. In all current theories for harmonic emission the essential dependence of the emissivity on the electric field strength $E$ of the plasma oscillations is $J \propto E^4$. Neglecting for the moment other weaker radial dependences, the $R^{-6.0}$ dependence of $J$ would imply a $R^{-1.5}$ variation of $E$ with radial distance from the sun. This radial variation of the plasma oscillation intensities is not nearly as steep as the $R^{-3.5}$ dependence reported recently by *Gurnett et al.* [1978*a*]. However, the plasma oscillation intensities given by *Gurnett et al.*

TABLE 1. The 36 Events Analyzed, With Associated Flare Coordinates and Calculated $J_0$ and $\alpha$ Values

| Date | Onset Time, UT | Flare Coordinates (Heliographic) Latitude | Flare Coordinates (Heliographic) Longitude | $J_0$, W m$^{-3}$ sr$^{-1}$ | $\alpha$ |
|---|---|---|---|---|---|
| Dec. 23, 1973 | 0800 | 16°S | 35°W | $6.84 \times 10^{-25}$ | − 5.8 |
| Jan. 18, 1974 | 0230 | 4°N | 65°W | $3.22 \times 10^{-25}$ | − 2.5 |
| April 5, 1974 | 1800 | 11°S | 35°W | $5.73 \times 10^{-25}$ | − 4.4 |
| May 8, 1974 | 0100 | 16°S | 3°E | $2.57 \times 10^{-26}$ | − 4.5 |
| May 9, 1974 | 2300 | 5°S | 45°W | $1.41 \times 10^{-26}$ | − 5.3 |
| Sept. 18, 1974 | 0530 | 9°N | 37°W | $2.17 \times 10^{-25}$ | − 5.4 |
| Sept. 18, 1974 | 1130 | 10°N | 42°W | $2.16 \times 10^{-25}$ | − 5.2 |
| Jan. 4, 1977 | 1720 | 22°S | 72°W | $1.47 \times 10^{-23}$ | − 6.2 |
| Oct. 10, 1977 | 2035 | 6°N | 10°E | $9.51 \times 10^{-25}$ | − 6.8 |
| Nov. 22, 1977 | 1000 | 23°N | 41°W | $3.25 \times 10^{-24}$ | − 8.7 |
| Dec. 7, 1977 | 0330 | 22°S | 16°W | $7.42 \times 10^{-23}$ | − 5.3 |
| Dec. 9, 1977 | 0650 | 24°S | 41°W | $2.48 \times 10^{-26}$ | − 9.8 |
| Dec. 23, 1977 | 0630 | 23°N | 6°E | $8.93 \times 10^{-28}$ | −11.0 |
| Dec. 24, 1977 | 1840 | 22°N | 12°W | $2.10 \times 10^{-25}$ | − 7.6 |
| Jan. 6, 1978 | 0730 | 35°N | 4°W | $3.52 \times 10^{-24}$ | − 3.7 |
| Jan. 8, 1978 | 0710 | 12°S | 85°W | $2.92 \times 10^{-25}$ | − 5.6 |
| Feb. 11, 1978 | 1430 | 14°N | 6°E | $5.12 \times 10^{-23}$ | − 8.5 |
| March 4, 1978 | 1200 | 18°N | 39°E | $4.88 \times 10^{-24}$ | − 9.3 |
| March 12, 1978 | 0210 | 20°N | 69°W | $9.15 \times 10^{-24}$ | − 4.7 |
| April 11, 1978 | 1410 | 22°N | 56°W | $5.06 \times 10^{-23}$ | − 4.4 |
| April 18, 1978 | 0100 | 14°N | 45°W | $6.10 \times 10^{-22}$ | − 5.6 |
| May 6, 1978 | 1635 | 19°N | 53°W | $2.20 \times 10^{-24}$ | − 5.1 |
| May 13, 1978 | 0750 | 28°S | 70°W | $1.90 \times 10^{-23}$ | − 5.6 |
| May 22, 1978 | 0200 | 27°S | 44°W | $1.96 \times 10^{-21}$ | − 2.8 |
| May 31, 1978 | 1620 | 21°N | 56°W | $4.21 \times 10^{-24}$ | − 8.4 |
| June 1, 1978 | 1330 | 21°N | 17°W | $1.81 \times 10^{-22}$ | − 3.8 |
| July 1, 1978 | 1145 | 21°N | 65°E | $1.35 \times 10^{-25}$ | − 4.3 |
| July 11, 1978 | 1050 | 20°S | 28°W | $2.95 \times 10^{-24}$ | − 5.9 |
| Sept. 8, 1978 | 1815 | 15°N | 64°W | $2.39 \times 10^{-24}$ | − 4.7 |
| Sept. 23, 1978 | 1010 | 34°N | 50°W | $5.01 \times 10^{-23}$ | − 4.6 |
| Oct. 5, 1978 | 1405 | 18°S | 4°E | $1.31 \times 10^{-26}$ | − 7.5 |
| Oct. 13, 1978 | 1235 | 18°S | 1°W | $7.29 \times 10^{-25}$ | − 6.5 |
| Oct. 31, 1978 | 0915 | 20°N | 36°W | $2.70 \times 10^{-26}$ | − 7.3 |
| Dec. 18, 1978 | 1630 | 11°N | 17°E | $2.62 \times 10^{-24}$ | − 5.4 |
| Feb.18, 1979 | 0650 | 19°N | 16°E | $7.57 \times 10^{-27}$ | − 7.8 |
| Feb. 18, 1979 | 1640 | 18°N | 16°W | $5.77 \times 10^{-24}$ | − 6.6 |

[1978*a*] are based on so few points it is probably not possible to make a meaningful quantitative comparison until more plasma oscillation events are analyzed. Such a study is currently under way. Nevertheless, it is interesting to note that the $R^{-1.5}$ variation implied by the above considerations agrees reasonably well with what would be expected for the saturation amplitude of plasma oscillations in the solar wind. Saturation effects are usually characterized by a dimensionless ra-

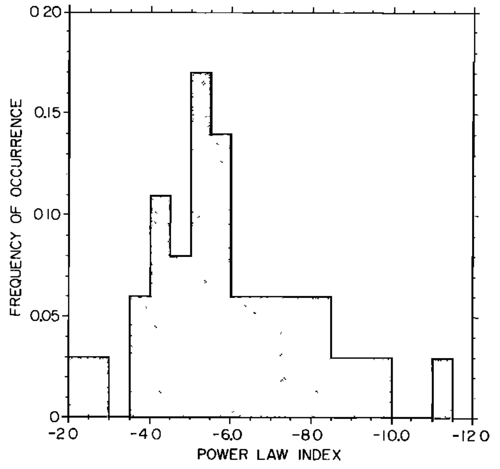

Fig. 2. A histogram of the power law indexes obtained from the 36 events analyzed. The highest frequency of occurrence is in the interval −4.0 to −6.0, and the average index is −6.0 ± 0.3. The standard deviation of the sample is 1.9.

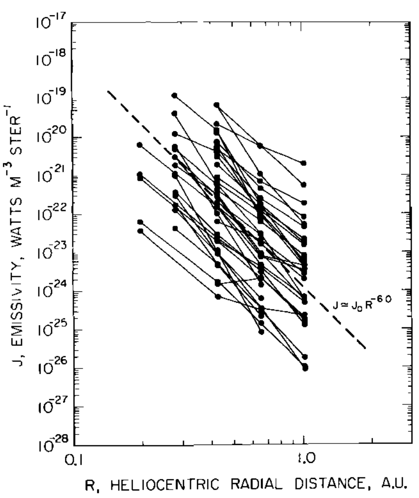

Fig. 3. A composite plot of the emissivity for the 36 events used in this study. Points common to one event are connected by a solid line, and the best fit power law is shown by a dashed line. This plot shows that the emissivity decreases rapidly with increasing radial distance from the sun.

tio of the electric field to plasma energy density, $E^2/8\pi nkT$, which reaches an approximately constant asymptotic value after the instability has grown into the nonlinear regime. Since the electron density varies approximately as $n \propto 1/R^2$, and the electron temperature varies approximately as $T \propto R^{-0.28}$ [*Hundhausen*, 1972], the saturation electric field strength should vary approximately as $E \propto R^{-1.14}$ if $E^2/8\pi nkT$ is constant, which is very close to the radial dependence estimated from the emissivity.

*Acknowledgments.* This research was supported by the National Aeronautics and Space Administration through contracts NAS5-11431 and NAS5-20093 and grant NGL-16-001-043 and by the U.S. Office of Naval Research.

The Editor thanks J. Fainberg for his assistance in evaluating this paper.

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(Received November 14, 1979;
revised February 8, 1980;
accepted February 11, 1980.)