

# ELECTROSTATIC TURBULENCE IN THE MAGNETOSPHERE

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Plasma wave measurements from the IMP-6, IMP-8 and Hawkeye-1 satellites show that a broad region of intense low-frequency electric field turbulence occurs on the high latitude auroral field lines at altitudes ranging from a few thousand kilometers in the ionosphere to many earth radii in the distant magnetosphere. A qualitatively similar, but less intense, type of electric field turbulence is also observed at the plasmopause during magnetic storms. In the auroral regions the turbulence occurs in an essentially continuous band on the auroral L-shells at all local times around the earth and is most intense during periods of auroral activity. In this paper we summarize the basic characteristics of this electric field turbulence and consider the possible role this turbulence may play in the heating and acceleration of plasma in the magnetosphere.

## I. INTRODUCTION

Recent studies of plasma wave measurements obtained from the IMP-6, IMP-8 and Hawkeye-1 satellites have revealed the existence of a broad region of low frequency electric field turbulence on auroral field lines at altitudes ranging from a few thousand kilometers in the auroral ionosphere to many earth radii in the distant magnetosphere [Gurnett and Frank, 1976; Gurnett *et al.*, 1976]. A similar region of electric field turbulence with somewhat lower intensities is also detected near the plasmopause during magnetic storms [Anderson and Gurnett, 1973]. The electric field intensity of the turbulence on the auroral field lines is often quite large, with maximum field strengths of about  $30 \text{ mV m}^{-1}$ . The frequency range of the electric field noise typically extends from about 10 Hz to a few kHz, with the maximum intensity at about 10 to 50 Hz. Weak bursts of magnetic noise are also detected in the same region as the electric field turbulence.

For many years it has been suggested that intense electric fields produced by current-driven instabilities can interact with the current-carrying particles in a plasma to produce an effective resistivity many orders of

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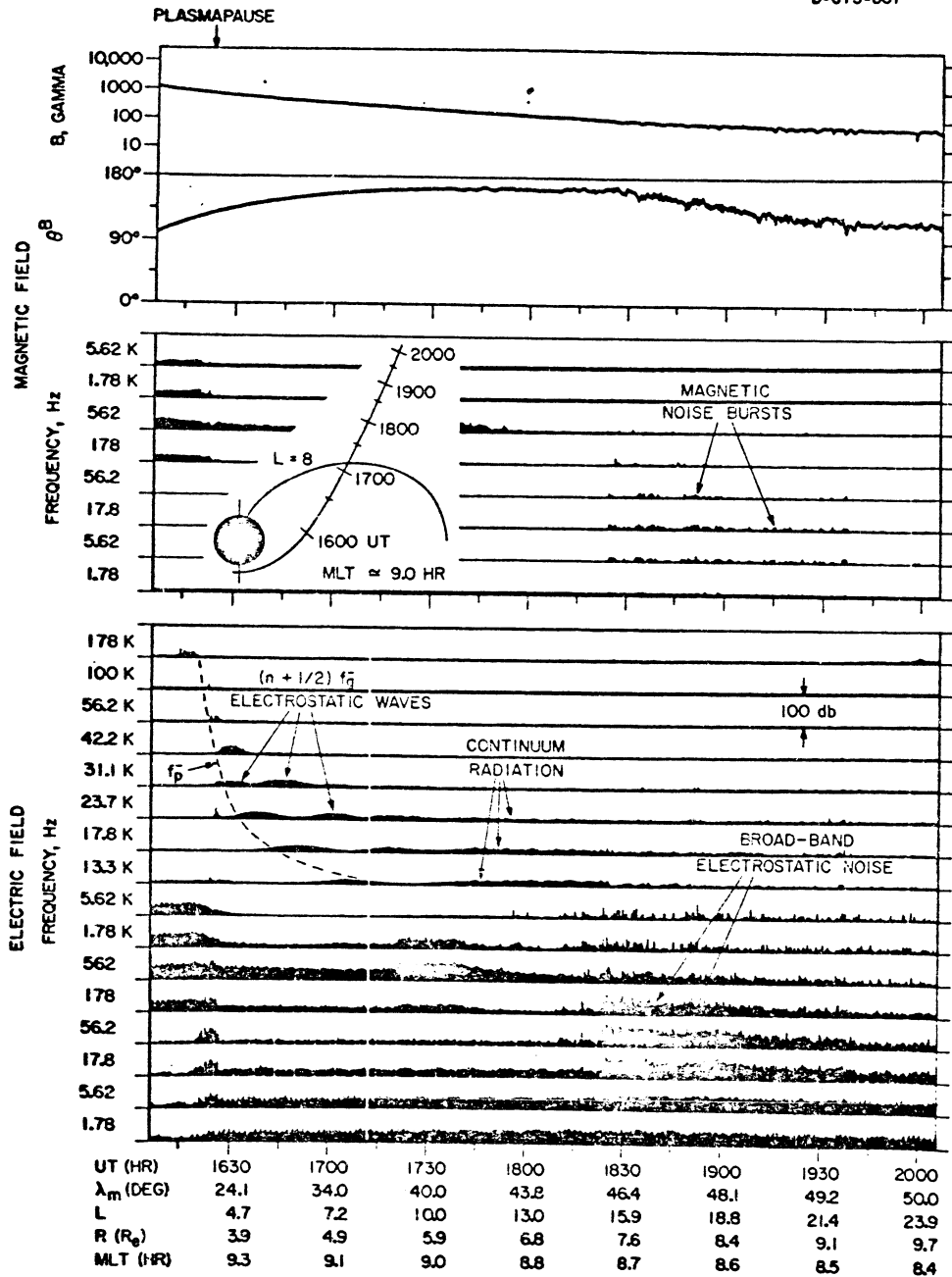
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magnitude larger than the Coulomb resistivity. (See for example the recent review by Mozer, 1976). Kindel and Kennel [1971] have considered the possible current-driven instabilities which could occur in the auroral zone and have concluded that the electrostatic ion cyclotron and ion acoustic modes should be unstable in the regions of field-aligned currents associated with the auroral electron precipitation. If the electric field turbulence produced by these instabilities grows to sufficiently large amplitudes the associated anomalous resistivity can produce large electrostatic potential differences along the magnetic field line, with an associated acceleration of some of the particles to high energies. In the distant magnetotail anomalous resistivity produced by plasma wave turbulence has also been suggested as a mechanism to control the merging rate of oppositely directed magnetic fields at X-type neutral lines [Piddington, 1967; Dungey, 1972]. In this paper we summarize the observed characteristics of the electric field turbulence detected by the IMP and Hawkeye satellites and consider the possible role of this turbulence in the heating and acceleration of auroral particles.

## II. ELECTROSTATIC TURBULENCE ON AURORAL FIELD LINES

To illustrate the principal characteristics of the intense low frequency electric field turbulence which occurs on the high latitude auroral field lines we first discuss the plasma wave measurements on three representative passes of the Hawkeye-1, IMP-6 and IMP-8 spacecraft. The Hawkeye-1 and IMP-6 passes in Figures 1 and 2 cut across the auroral L-shells relatively close to the earth (5 to 10  $R_e$ ) in the local morning and evening, respectively, and the IMP-8 pass in Figure 3 crosses through the neutral sheet region of the distant magnetotail about 30  $R_e$  from the earth. The top panel of each of these illustrations shows the magnetic field magnitude and direction and the middle and bottom panels show the plasma wave magnetic and electric field intensities. The intensity scale for each channel is proportional to the logarithm of the field strength, with a range of 100 db from the baseline of one channel to the baseline of the next higher channel. For the IMP data the dots give the peak field strength and the vertical bars give the average field strength. For further details of the plasma wave instrumentation on these spacecraft see Gurnett [1974] and Kurth et al. [1975].

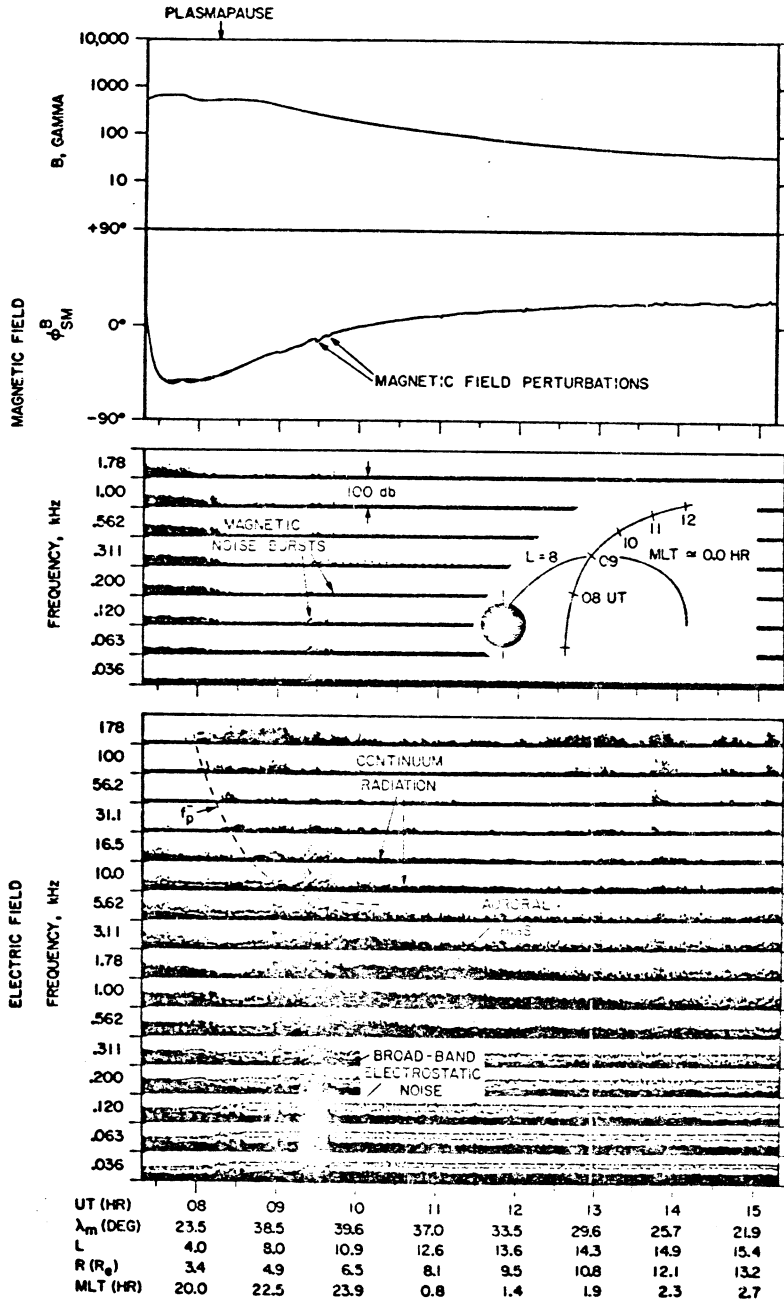
The first representative pass (in Figure 1) is an outbound Hawkeye-1 pass in the local morning at about 0900 magnetic local time. Several types of plasma waves are present during this pass. Within the plasmasphere, before about 1525 UT, plasmaspheric hiss is evident in both the electric and magnetic field channels at frequencies from 178 Hz to 5.62 kHz. At slightly higher frequencies outside of the plasmapause a series of  $(n + 1/2)f_g$  electrostatic cyclotron harmonic emissions and a band of continuum radiation can be seen extending over a large range of radial distances. Starting at about 1825 UT, and extending to about 1940 UT, a region of intense low-frequency electric field noise is evident in the frequency range from about 10 Hz to 10 kHz. Since this noise occurs over a broad range of frequencies and is most evident in the electric field data we refer to this noise as broad-band electrostatic noise [Gurnett et al., 1976; Gurnett and Frank, 1976]. Some



HAWKEYE-1, DAY 50, FEB 19, 1975

Figure 1. A Hawkeye-1 pass near local dawn. Intense electrostatic turbulence occurs near the plasmopause, from 1620 to 1625 UT and along the auroral field lines, from about 1825 to 1940 UT.

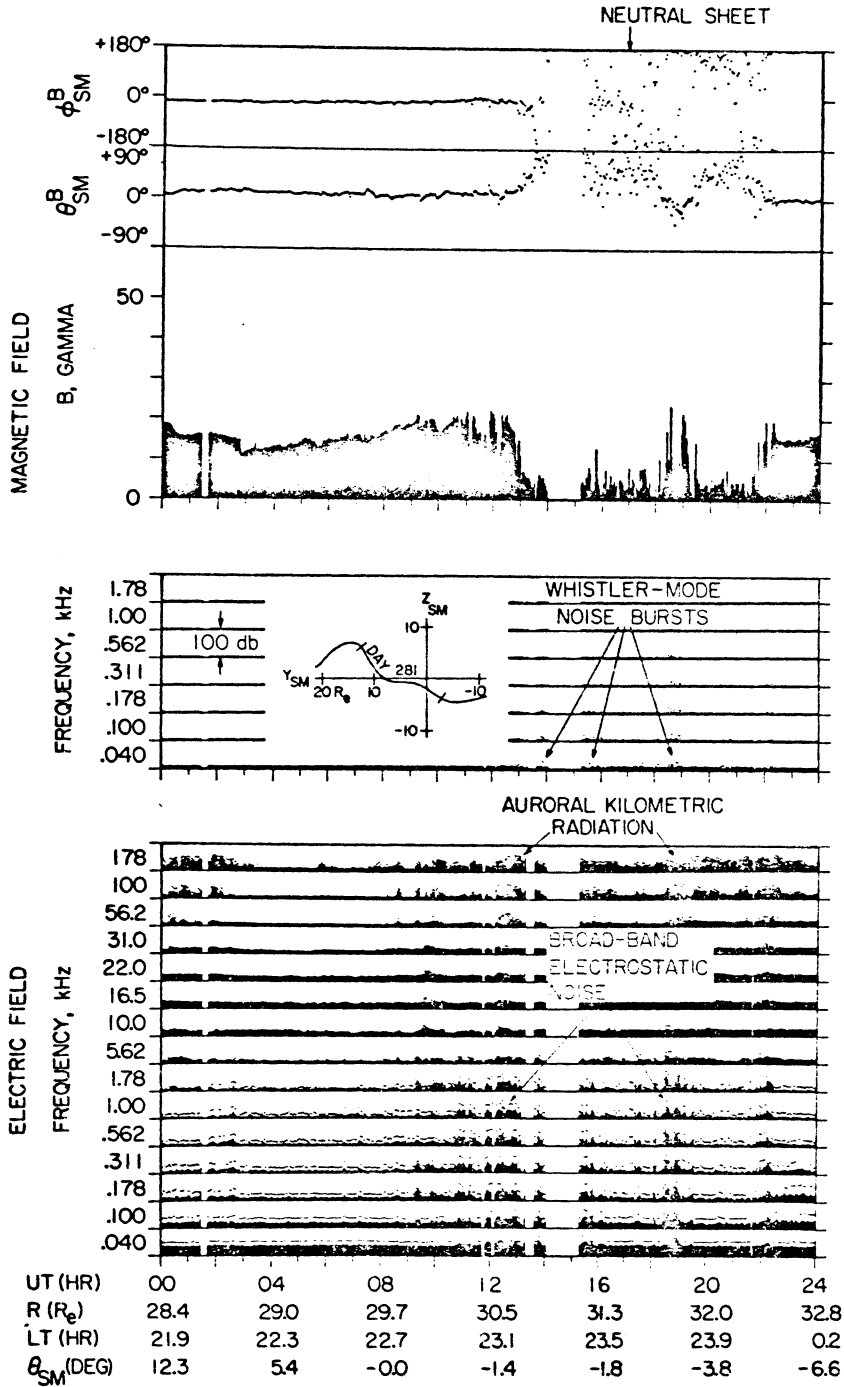
weak bursts of magnetic noise are also observed in the same region as the broad-band electrostatic noise. Simultaneous with the onset of the broad-band electrostatic noise in Figure 1 (at 1825 UT) an abrupt cutoff occurs in the continuum radiation in the 13.3 and 17.8 kHz channels. This cutoff



IMP-6, DAY 192, JULY 11, 1973

Figure 2. An IMP-6 pass near local midnight showing the occurrence of several regions of intense broad-band electrostatic noise.

indicates that the spacecraft has entered a region of distinctly higher plasmas density (with  $f_p \approx 17.8$  kHz) in the region where the broad-band electrostatic noise occurs. At the same time a distinct skewing of the magnetic field direction,  $\theta^B$ , and an increase in the magnetic field fluctuations are evident. Both the skewing of the magnetic field direction and the increase



TMP-8. DAY 281 OCT. 8. 1974

Figure 3. An IMP-8 pass through the plasma sheet in the distant magnetotail showing the occurrence of broad-band electrostatic noise near the outer boundary of the plasma sheet.

in the plasma density indicate that the spacecraft has entered a region of higher  $\beta$  (ratio of plasma to magnetic pressure) characteristic of the polar cusp or entry layer [Frank, 1971; Paschmann et al., 1976] on the day side of the magnetosphere.

On the night side of the magnetosphere a qualitatively similar type of plasma wave turbulence is also observed, both near the earth and in the distant magnetotail. Figure 2 shows a typical IMP-6 pass through the high-latitude region of the magnetosphere near the earth in the local evening, at about 2300 magnetic local time. During this pass several distinct regions with intense broad-band electrostatic noise can be identified, the first at about 0900 UT, followed by a broad region from about 0920 to 0940 UT. The enhanced electric field intensities within these regions, at L-values from about 8 to 10, are very clear and distinct, particularly in the peak field strength measurements. Magnetic noise bursts are also evident in the low frequency, 36 Hz to 200 Hz, magnetic field channels. Several distinct perturbations in the magnetic field direction,  $\varphi_{SM}^B$ , indicative of field-aligned currents, are also present in the region where the broad-band electrostatic noise is observed. Figure 3 shows an IMP-8 pass through the plasma sheet in the distant magnetotail for which the same type of broad-band electrostatic noise is observed at a radial distance of over  $30 R_E$  from the earth. During this pass the transition from the northern to the southern lobes of the magnetotail is indicated by the change in the magnetic field direction from  $\varphi_{SM}^B \simeq 0^\circ$  to  $\varphi_{SM}^B \simeq 180^\circ$  and the high energy density  $\beta \simeq 1$  region of the plasma sheet can be identified by the region of depressed magnetic field intensity from about 1300 to 2200 UT. Comparing the electric field intensities with the magnetic field magnitude  $B$  it is seen that the intense broad-band electrostatic noise tends to occur near the boundaries of the plasma sheet in the region where the magnetic field changes from the relatively steady field characteristic of the high latitude magnetotail to the depressed and more variable field in the plasma sheet. Detailed comparisons with the plasma measurements of Frank et al. [1976] for this same period show that the intense broad-band noise occurs in regions with large flow velocities,  $> 10^3$  km sec<sup>-1</sup>, associated with the merging region (fireball) in the distant magnetotail. Magnetic noise bursts, comparable to the events in Figures 1 and 2, are also evident in the regions of intense broad-band electrostatic noise. The onset of the broad-band electrostatic noise bursts at 1205, 1830 and 2200 UT, also occurs coincident with the onset of intense bursts of auroral kilometric radiation, a type of radio emission generated at low altitudes near the earth. This association strongly suggests that the plasma wave turbulence in the distant magnetosphere plays an important role in controlling or influencing the auroral particle precipitation near the earth.

Typical peak and average spectrums of the electric and magnetic fields in a region of intense broad-band electrostatic noise are shown in Figure 4. These spectrums show that the ratio of the average electric field energy density to the average magnetic field energy density is much greater than one,  $E^2/c^2 B^2 \simeq 39$ , which illustrates the essentially electrostatic (or quasi-electrostatic) character of the turbulence. The electric field spectrum in Figure 4 also shows that the frequency range of this turbulence extends from near the proton gyrofrequency,  $f_g^+$ , to the electron gyrofrequency,  $f_g^-$ . The largest electric field intensities occur at low frequencies, from about 10 to

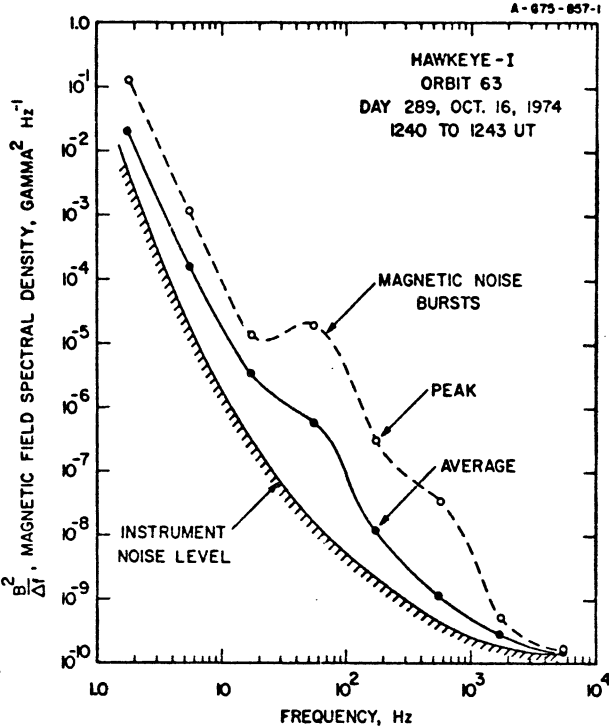
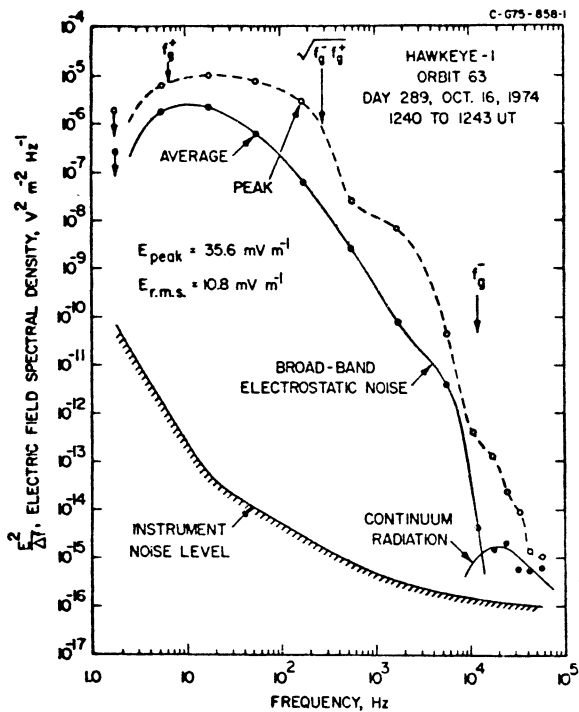


Figure 4. Representative electric and magnetic field spectrums in a region of intense broad-band electrostatic noise.

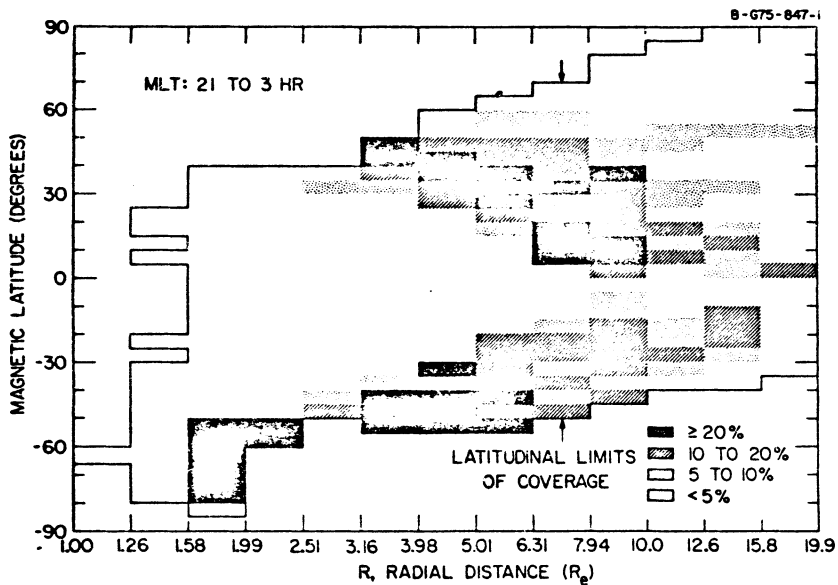


Figure 5. The frequency of occurrence of broad-band electrostatic noise in the region near local midnight.

50 Hz, in the range between  $f_{g+}^+$  and the hybrid frequency  $\sqrt{f_{g+}^+ f_{g-}^-}$ . The r.m.s. broad-band electric field strength for this case is  $10.8 \text{ mV m}^{-1}$  and the peak broad-band field strength is  $35.6 \text{ mV m}^{-1}$ .

Using the extensive measurements available from the IMP-6 and Hawkeye-1 spacecraft a detailed study has been made of the region of occurrence of the broad-band electrostatic noise. The essential features of the frequency of occurrence distribution are shown in Figures 5 and 6. For this frequency of occurrence distribution events are identified on the basis of the low-frequency electric field intensity (56.2 Hz for Hawkeye-1 and 63.0 Hz for IMP-6). The threshold electric field spectral density used for defining an event is  $1.4 \times 10^{-7} \text{ volt}^2 \text{ m}^2 \text{ Hz}^{-1}$ . Figure 5 shows the frequency of occurrence as a function of radial distance,  $R$ , and magnetic latitude,  $\lambda_m$ , for magnetic local time in the local midnight quadrant, from about 21 to 03 Hr. MLT. These data show that the broad-band electrostatic noise occurs in two distinct latitudinally symmetric regions, starting at high latitudes,  $\sim 70^\circ$ , near the earth and extending to progressively lower latitudes with increasing radial distance. The two regions appear to merge in the distant magnetotail at a radial distance of about  $10 R_e$ . The latitudinal width of the region of occurrence, approximately  $20^\circ$  at  $R = 5.01$  to  $6.31 R_e$ , is several times larger than the latitudinal width typically observed on an individual pass. This increase in the apparent latitudinal width of the region of occurrence is almost certainly caused by the orbit-to-orbit variations of the L-shell on which the noise occurs. On the basis of passes through the plasma sheet, as in Figure 3, in which the noise is observed near the outer boundaries of the plasma sheet, it seems likely that at any given time the northern and southern regions of occurrence remain distinctly separated to much larger distances ( $R \gg 10 R_e$ ) in the magnetotail than are indicated by the statistical survey in Figure 5.

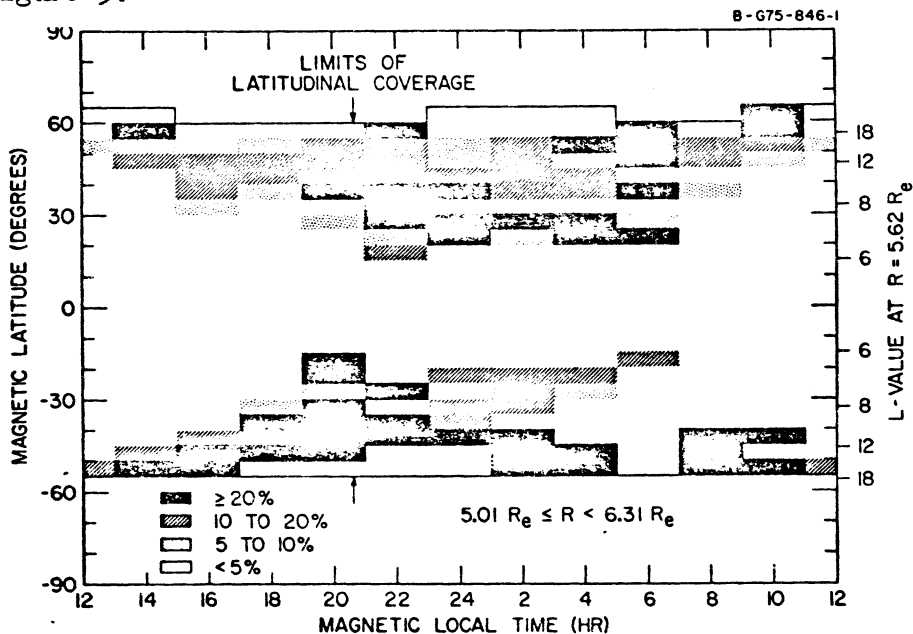


Figure 6. The frequency of occurrence of broad-band electrostatic noise on a shell of constant radial distance from  $5.01$  to  $6.31 R_e$ .



To illustrate the variations in the region of occurrence with magnetic local time Figure 6 shows the frequency of occurrence as a function of magnetic latitude and magnetic local time at a constant radial distance,  $5.01 R_e \leq R < 6.31 R_e$ . This range of radial distance was chosen because it is sufficiently far from the earth to provide measurements over a wide range of magnetic latitudes and still close enough for the magnetic field model to be reasonably accurate. For reference, the L-value of the magnetic field passing through the center of this region at  $R = 5.62 R_e$  is shown on the right side of Figure 6. The broad-band electrostatic noise is seen to occur in an essentially continuous band at all local times around the earth. The noise occurs at the lowest magnetic latitudes near local midnight and at systematically higher magnetic latitudes on the day side of the earth. The frequency of occurrence (and also the average intensity, not shown) is significantly higher on the night side of the earth. Near local midnight the maximum occurrence is at L-values from about 8 to 12.

### III. ELECTROSTATIC TURBULENCE NEAR THE PLASMAPAUSE

Electrostatic turbulence similar to the intense broad-band electrostatic noise observed along the auroral field lines is also observed near the plasmopause during magnetic storms. A good example of this electrostatic turbulence is evident in the 17.8 and 56.2 Hz electric field channels of Figure 1 as the spacecraft crosses the plasmopause, from about 1620 to 1625 UT. The broad-band field strength of this noise is relatively weak, only about  $250 \mu\text{V m}^{-1}$ . No magnetic field can be detected in the corresponding magnetic field channels. As with the broad-band electrostatic noise in the auroral zone the electric field energy density of the plasmopause noise greatly exceeds the magnetic field energy density (for example, compare this noise with the electromagnetic plasmaspheric hiss emissions in the 178 Hz channel at 1615 UT).

Electrostatic noise of the type illustrated in Figure 1 has been previously observed on the S<sup>3</sup>-A spacecraft [Anderson and Gurnett, 1973] near the equatorial plane during a magnetic storm and similar electrostatic waves have also been observed at low altitudes near the plasmopause in association with a stable red arc [Nagy et al., 1972]. The Hawkeye-1 observations indicate that this plasmopause electrostatic turbulence occurs all along the magnetic field line, from the equator to low altitudes in the ionosphere. At the present time relatively little is known in detail about the occurrence of this electrostatic turbulence, or its relationship to the plasma interactions occurring at the plasmopause during a magnetic storm.

### IV. SUMMARY AND DISCUSSION

Intense low-frequency electrostatic turbulence is observed in two distinct regions of the magnetosphere: along the auroral field lines and near

the plasmopause. Along the auroral field lines this electric field turbulence, which has been called broad-band electrostatic noise, is very intense with maximum broad-band electric field strengths sometimes as large as  $30 \text{ mV m}^{-1}$ . This turbulence occurs in an essentially continuous band on the auroral L-shells at all local times around the earth and extends to large distances ( $> 40 R_e$ ) in the distant magnetotail near the outer boundary of the plasma sheet. Weak bursts of magnetic noise are also observed in the same region as the broad-band electrostatic field and comparisons with magnetic field and plasma measurements show that this noise occurs on field lines which carry significant field-aligned currents between the distant magnetosphere and the ionosphere and in regions of the distant magnetotail which have large plasma flow velocities,  $> 10^3 \text{ km sec}^{-1}$  [Gurnett et al., 1976]. At low altitudes evidence has been presented [Gurnett and Frank, 1976] indicating that this low frequency electric field turbulence occurs on the same magnetic field lines as the intense inverted-V electron precipitation events responsible for a major fraction of the auroral energy dissipation in the local evening. These relationships are summarized in Figure 7. Near the plasmopause a lower intensity type of electrostatic turbulence is observed which has many characteristics (broad-band, quasi-electrostatic, peak intensity from 10 to 50 Hz) similar to the broad-band electrostatic noise observed in the auroral regions. This noise occurs relatively infrequently and is apparently associated with the interaction of the hot ring current plasma with the plasmasphere during magnetic storms.

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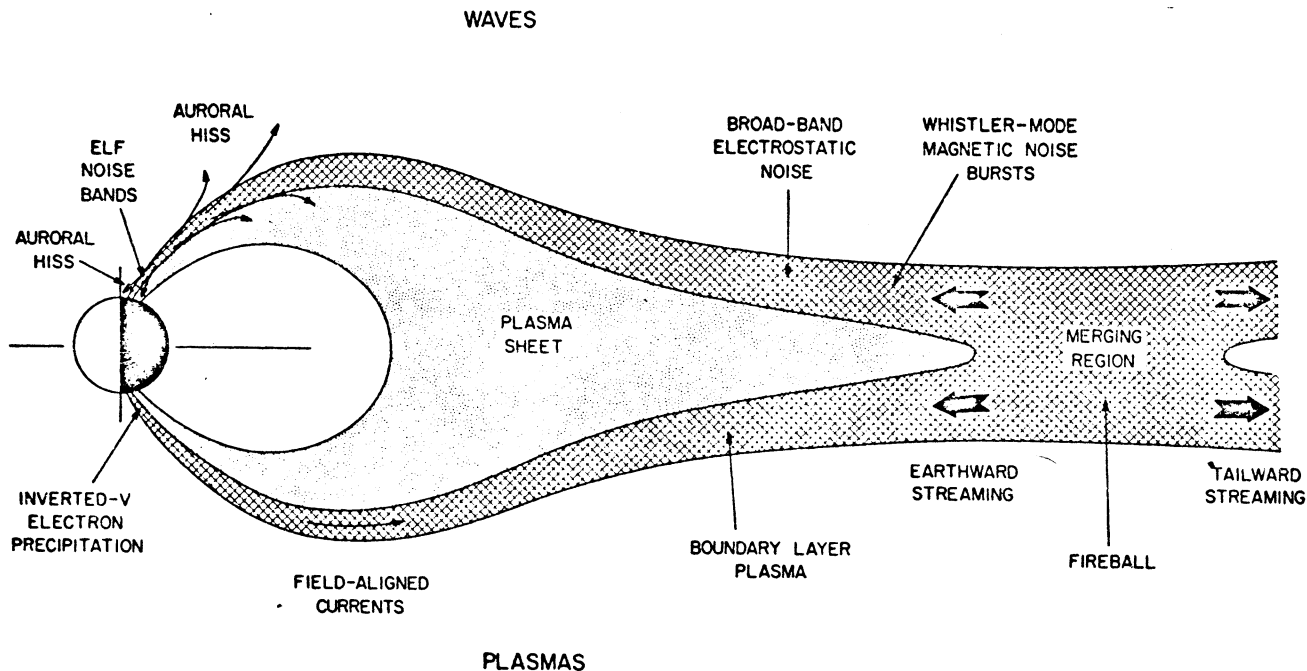


Figure 7. A qualitative model showing the region where the broad-band electrostatic noise occurs in relation to the plasma sheet near local midnight.

Although most of the general features of the electric field turbulence which occurs in the auroral regions and distant magnetotail are now known many questions remain concerning the plasma wave modes involved in this turbulence and the role which these waves play in the plasma heating and acceleration which occur along the auroral field lines. Since this turbulence occurs in regions with substantial field-aligned currents it seems most likely that these waves are produced by a current driven instability, such as the ion sound wave mode ( $f < f_p^+$ ) or the electrostatic ion cyclotron modes ( $f \simeq n f_g^+$ ). Current driven instabilities of this type have been studied by several investigators (see for example, Kindel and Kennel, 1971). Further detailed studies of the charged particle distribution functions are needed to identify the plasma instabilities involved in the generation of these waves. Rough estimates of the anomalous resistivity produced by the broadband electric field turbulence detected in regions of field-aligned currents at high altitudes ( $R > 4R_e$ ), indicate that this turbulence could only account for potential differences of about 100 volts between  $R \simeq 4.0 R_e$  and the distant magnetosphere [Gurnett and Frank, 1976]. Unless the turbulence becomes stronger at lower altitudes these potential differences are too small to account for the acceleration of auroral electrons to energies of 10 keV. Measurements are still needed in the altitude range from about 1.8 to 4.0  $R_e$  to provide a conclusive evaluation of the role of this turbulence on the acceleration of auroral particles.

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