

# Correlation of Bow Shock Plasma Wave Turbulence With Solar Wind Parameters

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The rms field strengths of electrostatic and electromagnetic turbulence in the earth's bow shock, measured in the frequency range 20 Hz to 200 kHz with the Imp 6 satellite, are found to correlate with specific solar wind parameters measured upstream of the bow shock. The largest rms field strengths of electrostatic turbulence (200 Hz to 4 kHz) occur when the upstream electron to proton temperature ratio  $T_e/T_p$  is large and when the proton temperature  $T_p$  is small, an indication that the mechanism for generating electrostatic turbulence in the bow shock is more efficient when lower upstream proton temperatures occur. No substantial correlation is found between the rms field strengths of electrostatic turbulence and three upstream parameters commonly used to classify the magnetohydrodynamic structure of the turbulent bow shock: the Alfvén Mach number  $M_A$ , the ratio of particle pressure to magnetic field pressure  $\beta$ , and the shock normal angle  $\psi(\mathbf{B}, \hat{n})$ . The strong correlation with  $T_e/T_p$  and  $T_p$  and the lack of strong correlation with  $M_A$ ,  $\beta$ , and  $\psi(\mathbf{B}, \hat{n})$  indicate that the strength of electrostatic turbulence in the bow shock is determined by the kinetic properties of the solar wind plasma rather than by its fluid properties. The largest rms field strengths for electromagnetic turbulence (20 Hz to 4 kHz) occur when the upstream particle density  $N$  is large and when the shock normal angle  $\psi(\mathbf{B}, \hat{n})$  is closer to 90°, this result supporting a previous conclusion that whistler waves comprise the electromagnetic turbulence in the bow shock. Electric field turbulence, composed of both electrostatic and electromagnetic fluctuations, correlates with the upstream parameters  $T_e/T_p$ ,  $T_p$ , and  $\psi(\mathbf{B}, \hat{n})$  in such a way as to imply that mode coupling occurs between electrostatic and electromagnetic waves. A broad spectrum of high-frequency (3–30 kHz) electrostatic turbulence typically observed in the leading edge of the bow shock is interpreted as indicating the region of electron heating. Deeper within the shock transition the intensity of low-frequency (<3 kHz) electrostatic turbulence greatly increases to form a broad peak, centered between 200 and 800 Hz, and is interpreted as corresponding to the region of maximum proton heating. The characteristic development of the electric field spectrum through the shock transition indicates that strong coupling exists between the electron and proton heating processes.

## INTRODUCTION

Several studies of the earth's bow shock have shown that a complex structure of wave-particle interactions governs the heating of solar wind electrons and ions as they stream across the shock transition. *Fredricks et al.* [1968, 1970a, b] have shown that electrostatic turbulence at 1.3 kHz and the scattering of protons correlate with the gradients in the magnetic field at the shock front, this evidence indicating the presence of a current-driven instability. *Montgomery et al.* [1970] and *Formisano and Hedgecock* [1973a, b] have shown that electron thermalization occurs in a thin region upstream of the bow shock, followed by ion thermalization in the main shock transition. Solar wind ions are reported by *Neugebauer* [1970] to be substantially decelerated near the upstream side of the bow shock, possibly by a charge separation electric field. *Neugebauer et al.* [1971] have reported the observation of ELF magnetic field oscillations (10–1000 Hz) correlated with superthermal electrons (>100 eV) in the shock magnetic field gradient. *Holzer et al.* [1966, 1972] and *Olson et al.* [1969] have discussed the spectrum of magnetic field fluctuations in the bow shock below about 100 Hz, which shows a broad noise spectrum with a peak near 3 Hz and includes waves that propagate in the shock frame both upstream and downstream. *Fairfield* [1974] has studied whistler waves in the frequency range 0.5–4.0 Hz which are detected ahead of the bow shock and may result from resonant interactions with upstream electrons. The spectrum of plasma wave turbulence in the bow shock, as measured with the University of Iowa plasma wave spectrum analyzers on the Imp 6 satellite, was reported by *Rodriguez and Gurnett* [1975]. Whistler waves and electrostatic waves are shown by Rodriguez and Gurnett to be the major

components of the bow shock spectrum between 20 Hz and 200 kHz.

In our previous report [*Rodriguez and Gurnett*, 1975], hereafter referred to as paper 1, it was shown that the characteristic electric field spectrum of the bow shock can be resolved into a low-frequency electromagnetic component (20–200 Hz) which decreases monotonically with increasing frequency approximately as  $f^{-2.0 \pm 0.5}$  and a higher-frequency electrostatic component (200 Hz to 4 kHz) which is associated with a peak in the electric field spectrum between about 200 and 800 Hz. The characteristic magnetic field spectrum of the bow shock was shown to decrease monotonically with frequency approximately as  $f^{-4.0 \pm 0.5}$  and to display an upper cutoff frequency near the electron gyrofrequency. By taking the ratio  $\epsilon_E/\epsilon_B$  of simultaneously measured electric and magnetic field energy densities in the bow shock it was shown in paper 1 that  $\epsilon_E/\epsilon_B$  increased nearly monotonically from values near  $10^{-4}$ – $10^{-3}$  at 20 Hz to values near  $10^{-2}$ – $10^{-3}$  at 1 kHz. The values of  $\epsilon_E/\epsilon_B$  (proportional to  $n^{-2}$ , where  $n$  is the index of refraction) at low frequencies and the observed upper cutoff frequency near the electron gyrofrequency in the shock magnetic field spectrum led to the conclusion in paper 1 that in the range 20–200 Hz the electric and magnetic field turbulence in the shock is caused by electromagnetic whistler waves. It was also concluded that the large values of  $\epsilon_E/\epsilon_B$  at frequencies greater than about 200 Hz showed that these higher-frequency waves are almost completely electrostatic and are associated with the peak centered between 200 and 800 Hz in the shock electric field spectrum.

The frequency range (20 Hz to 200 kHz) of the shock plasma wave spectra discussed in paper 1 includes all the characteristic plasma frequencies for electrons and protons except for the proton gyrofrequency (~0.1 Hz). The heating of solar wind electrons and protons in the bow shock must result in the self-consistent generation of a spectrum of turbulent

electric fields. It is expected that such a spectrum will be broad enough to include most of the characteristic plasma frequencies, since these are the elementary excitations through which the particle velocity distributions can be broadened. Therefore it is assumed that the electric field spectra of paper 1 and of this study are closely related to the dissipative processes that occur in the bow shock.

#### INTENSITY VARIABILITY OF SHOCK TURBULENCE

**Dynamic range.** The variability of plasma wave turbulence in the bow shock is indicated in Figures 1 and 2 (similar to Figures 7 and 8 of paper 1). In Figure 1, two kinds of electric field spectra are shown: spectra measured with a 5.12-s averaging time (averages) and spectra measured with a 0.1-s averaging time (peaks). One measurement of the peak spectrum is obtained within the time period of one measurement of the average spectrum. (A description of the University of Iowa plasma wave experiment and the spectrum analyzer used to measure the electric and magnetic field spectra in the bow shock is given in paper 1.) The left-hand side of Figure 1 is an overlay of average electric field spectra that were measured in 36 crossings of the bow shock; the right-hand side is an overlay of the corresponding peak electric field spectra. Figure 1 thus illustrates the dynamic range of intensities that have been sampled for electric field turbulence in the bow shock. For example, on different shock crossings the average electric field spectral densities at 1 kHz range from a minimum of  $3 \times 10^{-19} \text{ V}^2 \text{ m}^{-2} \text{ Hz}^{-1}$  to a maximum of  $6 \times 10^{-9} \text{ V}^2 \text{ m}^{-2} \text{ Hz}^{-1}$ , a dynamic range of over 4 orders of magnitude. A similar range of variation is seen in the peak spectral densities. For each spectrum of Figure 1 a total rms field strength  $E_{\text{rms}}$  may be computed by integrating the spectrum from 20 Hz to 200 kHz. The range of  $E_{\text{rms}}$  so obtained is  $(4.0\text{--}0.19) \times 10^{-3} \text{ V m}^{-1}$  for

the average spectra and  $(23\text{--}2.1) \times 10^{-3} \text{ V m}^{-1}$  for the peak spectra. The electrostatic and electromagnetic components of the shock spectrum which were described above are evident in the characteristic shape of the spectra of Figure 1, with the best resolution of the two components occurring in the average spectra of intermediate intensity. For average spectra of greatest intensity it can be seen that the peak centered between 200 and 800 Hz broadens out enough to nearly fill in the minimum in the curve at about 200 Hz where the two components of the spectrum meet. For the average spectra of smallest intensity the peak nearly disappears.

Figure 2 shows the average and peak magnetic field spectra corresponding to, and having the same format as, the average and peak electric field spectra of Figure 1. There is evidently a smaller dynamic range for the magnetic field spectral densities (about 2 orders of magnitude at 100 Hz), and except for a few peak spectra the shape of the spectrum has the characteristic monotonic decrease with frequency associated with the component below about 200 Hz in the electric field spectrum. The plasma wave turbulence associated with the broad peak in the average spectra of Figure 1 is clearly electrostatic turbulence, since there is no corresponding peak in the magnetic field spectra of Figure 2.

**Correlation parameters.** Since plasma shock waves are usually categorized in terms of such upstream parameters as the Alfvén Mach number  $M_A$ , the ratio of particle pressure to magnetic field pressure  $\beta$ , the ratio of electron to proton temperatures  $T_e/T_p$ , and the shock normal angle  $\psi(\mathbf{B}, \hat{n})$ , it is of interest to investigate the relationship between these parameters and the intensity variability of bow shock turbulence indicated by Figures 1 and 2. The upstream parameters used in this study are derived from the measurements of two other Imp 6 experiments, the Los Alamos Scientific Laboratory

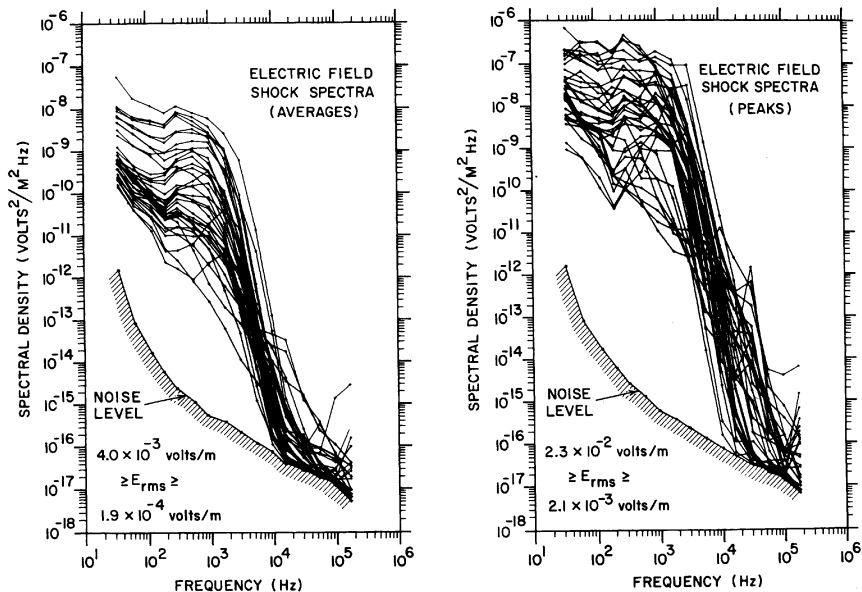


Fig. 1. The intensity variability of bow shock electric field turbulence is indicated by the representative sample of shock spectra obtained in 36 crossings of the bow shock. The average spectra are 5.12-s averages, and the peak spectra are 0.1-s averages.  $E_{\text{rms}}$  is the rms electric field strength obtained by integrating a given spectrum from 20 Hz to 200 kHz.

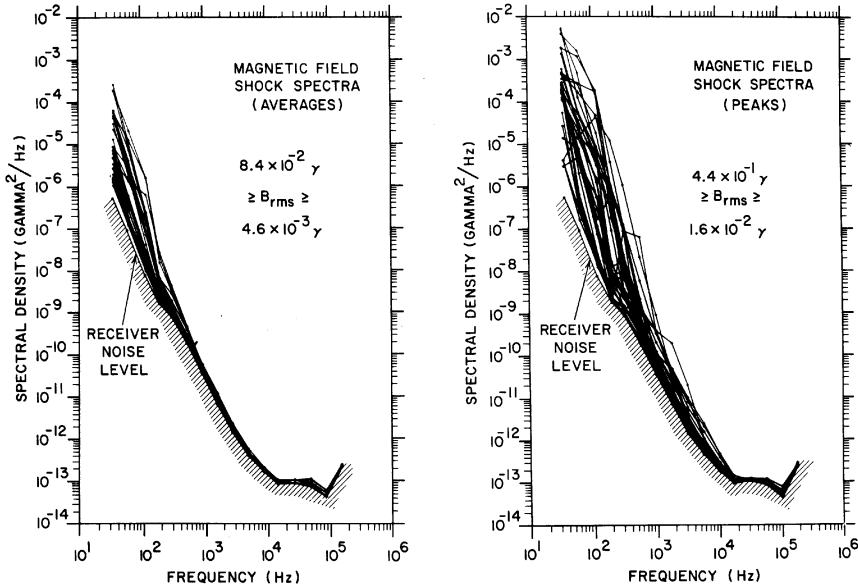


Fig. 2. The intensity variability of bow shock magnetic field turbulence is represented by average and peak spectra obtained for the same 36 shock crossings shown in Figure 1.  $B_{rms}$  is the rms magnetic field strength.

plasma analyzer, which provides a measurement of the velocity distribution of solar wind particles with a minimum time resolution of about 90 s, and the Goddard Space Flight Center (GSFC) magnetometer, which measures the magnetic field magnitude and direction with a time resolution of 80 ms. In addition to  $M_A$ ,  $\beta$ ,  $T_e/T_p$ , and  $\psi(\mathbf{B}, \hat{n})$ , other upstream parameters used are the upstream magnetic field magnitude  $|\mathbf{B}|$ , the magnetosonic Mach number  $M_s$ , the solar wind velocity  $V_{sw}$ , the Alfvén speed  $C_A$ , the sound speed  $C_s$ , and the particle density  $N$ . The rms field strengths for the electromagnetic and electrostatic components in 5.12-s average shock spectra like those in Figures 1 and 2 are used as the measure of the intensity of shock turbulence. We define  $E_{rms,1}$  and  $E_{rms,2}$  as the rms electric field strengths obtained from the average shock electric field spectrum by integrating from 20 to 200 Hz and from 200 Hz to 4 kHz, respectively.  $E_{rms,1}$  and  $E_{rms,2}$  are thus the rms electric field strengths of the electromagnetic and electrostatic components, respectively, of the shock electric field spectrum.  $B_{rms}$  is the rms magnetic field strength of the electromagnetic component, obtained by integrating the average shock magnetic field spectrum from 20 Hz to 4 kHz. The approach of this study is to seek correlation between the values of  $E_{rms,1}$ ,  $E_{rms,2}$ , and  $B_{rms}$  and the values of  $M_A$ ,  $M_s$ ,  $\beta$ ,  $T_e/T_p$ ,  $V_{sw}$ ,  $C_A$ ,  $C_s$ ,  $N$ ,  $T_e$ ,  $T_p$ ,  $\psi(\mathbf{B}, \hat{n})$ , and  $|\mathbf{B}|$ .

Simultaneous measurement of the spectrum of bow shock turbulence and upstream solar wind parameters is not possible with a single satellite, so the solar wind parameters derived from the plasma analyzer measurements are averages over time periods during which Imp 6 was in the upstream region near the bow shock. The solar wind parameters are averaged over 1- to 2-hour periods, before or after the shock crossing at which the corresponding plasma wave spectrum is measured, to obtain values which characterize the solar wind properties near the time of the shock crossing. The 1- to 2-hour averaging

periods also make the solar wind parameters relatively independent of short-period fluctuations. If multiple shock crossings take place in a time interval less than the averaging times of solar wind parameters, the corresponding series of rms field strengths for shock turbulence is averaged over the number of crossings. The values of shock normal angles  $\psi(\mathbf{B}, \hat{n})$  are computed from the model of Fairfield [1971], using 4-s averages of the GSFC magnetometer measurements near the leading edge of each shock crossing.

The distributions of values for the upstream parameters used in this study are shown in the histograms of Figures 3 and 4. The general shapes of the distributions compare favorably with the corresponding distributions which are obtained for the solar wind when many more samples are taken [Formisano and Moreno, 1974]. The solar wind parameters of the present study thus approximate the typical ranges of solar wind conditions. The minimums, maximums, means, and standard deviations for the distributions of Figures 3 and 4 are listed in Table 1.

Energy densities for the electromagnetic and electrostatic components of the bow shock spectrum may be computed from  $\epsilon(E_{rms,i}) = E_{rms,i}^2/8\pi$  ( $i = 1, 2$ ) and  $\epsilon(B_{rms}) = B_{rms}^2/8\pi$ , where Gaussian units are used for the electric and magnetic fields. The relationship of  $\epsilon(E_{rms,i})$  and  $\epsilon(B_{rms})$  to the solar wind energy density

$$\epsilon(sw) = \frac{1}{2}Nm_pV_{sw}^2 + \frac{1}{2}NK_B(T_e + T_p)$$

where  $m_p$  is the proton mass and  $K_B$  is Boltzmann's constant, is indicated by the distributions of the ratios  $\epsilon(E_{rms,i})/\epsilon(sw)$  and  $\epsilon(B_{rms})/\epsilon(sw)$  shown in Figure 5. It is evident that the plasma wave energy densities in the bow shock are always very small fractions of the solar wind energy density. The absolute energy density distributions for the bow shock electromagnetic and electrostatic components and for the solar wind are shown

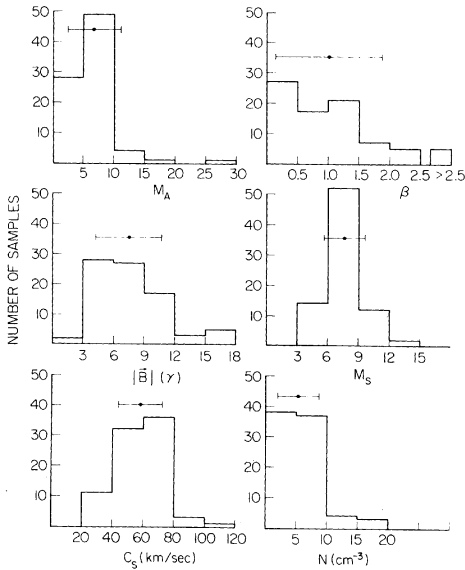


FIG. 3. The distributions of values for solar wind parameters used in the present study. The mean and standard deviations for each distribution are indicated by the dot and error bars, respectively.

in Figure 6. Table 2 lists the characteristic parameters for the distributions of Figures 5 and 6.

**Linear correlation coefficients.** A standard statistical correlation technique (least squares fitting) has been used to calculate linear correlation coefficients that indicate the degree of association between the rms field strength of shock turbulence and solar wind parameters. The fitting equation used is  $\log y =$

TABLE 1. Solar Wind Parameter Characteristics

	Min	Max	Mean	Standard Deviation
$M_A$	1.5	26.6	6.8	4.7
$\beta$	0.03	4.5	1.02	0.87
$ B , \gamma$	2.0	16.9	7.5	3.2
$M_s$	3.9	12.5	7.8	1.9
$C_s, \text{km/s}$	33.2	105.	58.	14.
$N, \text{cm}^{-3}$	0.5	19.0	5.2	3.4
$C_A, \text{km/s}$	15.4	278.	88.	60.
$\psi(B, \hat{n}), \text{deg}$	11.7	90.	60.	19.
$T_e/T_p$	0.65	9.0	2.6	1.8
$V_{sw}, \text{km/s}$	315.	660.	431.	63.
$T_e \times 10^5 \text{ }^\circ\text{K}$	0.6	6.0	1.6	0.80
$T_p \times 10^5 \text{ }^\circ\text{K}$	0.15	3.0	0.98	0.72

$bx + a$ , where  $y$  is the rms field strength,  $x$  is the plasma parameter, and  $b$  and  $a$  are constants. The choice of fitting equation is not based on any theoretical relationship between the parameters but is used only to provide a quantitative measure (the correlation coefficient) with which to judge the statistical dependence (or independence) of the parameters involved. Since the measurements of electric and magnetic field amplitudes are obtained from antenna voltages which are digitized with equal quantizing steps on a logarithmic scale, the relative uncertainty  $\Delta V/V$  in the measured signal voltages is constant. Therefore the least squares fitting is done with constant relative uncertainty in the rms field amplitudes [Bevington, 1969, p. 180].

Table 3 lists the linear correlation coefficients  $R$  obtained for the two-parameter fits. For  $S$  points used in the least squares fit,  $R_c$  is the critical value of the correlation coefficient at the 1% level of significance for a two-parameter fit [Neville and Kennedy, 1964, p. 314]. If the absolute value of the computed correlation coefficient  $|R|$  exceeds  $R_c$ , the probability is 1% that the observed correlation between the two parameters is due to chance alone. Therefore a strong correlation is indicated by a large value of  $R$  compared to  $R_c$ .

#### ELECTROSTATIC TURBULENCE

A study of the coefficients in Table 3 reveals that the electrostatic field strength  $E_{rms,2}$  is strongly correlated with several of the solar wind parameters. In particular,  $E_{rms,2}$  and  $T_e/T_p$  have the largest value of  $R$ , an indication that a strong positive correlation exists between the intensity of electrostatic turbulence in the bow shock and the electron to proton temperature ratio in the upstream solar wind. Figure 7 shows the plot of  $E_{rms,2}$  against  $T_e/T_p$ . The diagonal dashed line in Figure 7 is the line of regression for  $E_{rms,2}$  on  $T_e/T_p$ , and the slope of this line indicates the apparent dependence of  $E_{rms,2}$  on  $T_e/T_p$ . The large error bars are at  $\pm\sigma(y)$ , the standard deviation, above and below the line of regression and indicate the degree of dispersion of the data points about the mean. However, in this case the large dispersion does not mean that large measurement errors are present in the values of  $E_{rms,2}$ . The dispersion of the values of  $E_{rms,2}$  is probably indicative of the dependence of  $E_{rms,2}$  on other parameters besides  $T_e/T_p$  which are not included in the two-parameter fit. As is shown in Table 3,  $E_{rms,2}$  displays significant correlation ( $R > R_c$ ) with other shock parameters, so that the total dependence of  $E_{rms,2}$  is very likely a complex function of  $T_e/T_p$ ,  $T_p$ ,  $C_s$ , etc. Also, the 1- to 2-hour averaging period for the solar wind parameters removes short-period fluctuations from these upstream values which may be related to some of the scatter in  $E_{rms,2}$ . In addition, the electric

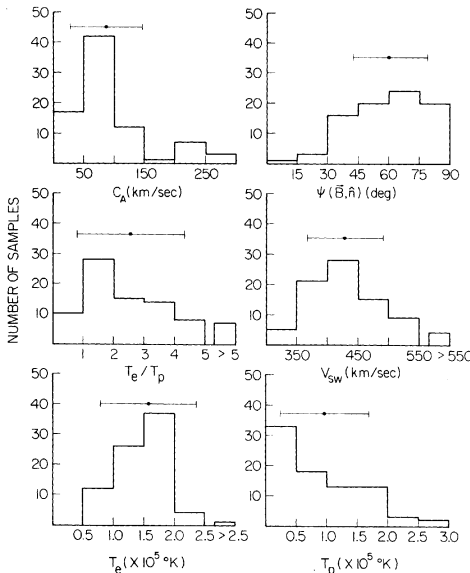


FIG. 4. The distributions of values for solar wind parameters used in the present study, similar to Figure 3. Means and standard deviations are indicated as in Figure 3.

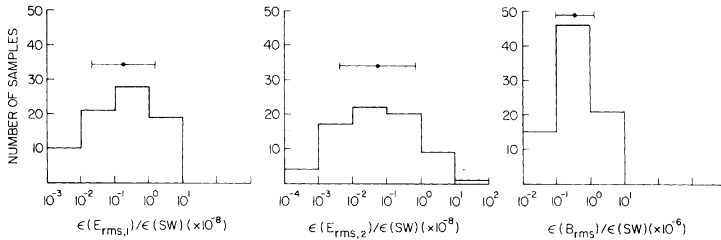


Fig. 5. The distributions of the ratios of plasma wave energy densities to the solar wind energy density. The logarithmic mean values and standard deviations of the ratios are indicated on the plots.

field measurements are made with a single antenna so that only one component of the electric field is detected at any instant. However, as was shown in paper 1, the electric field turbulence in the bow shock has a broad angular distribution, and a measurement averaged over 5.12 s (approximately one half the spin period) can be assumed to be close to the total field magnitude. Considering then the approximations involved in a two-parameter fit, it can be expected that a true but weak dependence of  $E_{rms,2}$  on an upstream parameter may not emerge from the correlations in this study. However, a strong, and therefore more important, dependence of  $E_{rms,2}$  on an upstream parameter should be evident in the correlations, even though the functional relationship between  $E_{rms,2}$  and the upstream parameter is not known. The slope of the regression line is the important measure of association between  $E_{rms,2}$  and  $T_e/T_p$ , and since the regression line is a mean fit, the standard deviation of the mean,  $\sigma(\bar{y})$ , is a better measure of dispersion because this tends to compensate for correlations not included in a two-parameter fit. The smaller error bars in Figure 7 are at the 1% level of significance,  $\pm 2.576\sigma(\bar{y})$ . At their location on the regression line the small error bars also indicate the 1% limits to the dispersion of the slope when the regression line is

rotated about its centroid. It is clear that the slope of the regression line changes neither in sign nor greatly in magnitude at these two limits.

The second-strongest correlation of  $E_{rms,2}$  is with the proton temperature  $T_p$ . The plot of  $E_{rms,2}$  against  $T_p$  is shown in Figure 8, where the line of regression for the two-parameter fit is the diagonal dashed line and the error bars have the same meaning as in Figure 7. The slope of the regression line indicates that a negative correlation exists between electrostatic turbulence in the bow shock and the upstream proton temperature. Since no significant correlation is found between  $E_{rms,2}$  and the electron temperature  $T_e$ , it appears that in the relationship between  $E_{rms,2}$  and the ratio  $T_e/T_p$  of Figure 7, variations in the upstream proton temperature  $T_p$  are the significant factor. Therefore we conclude that the instability mechanism that produces electrostatic turbulence in the bow shock is primarily associated with the value of  $T_e/T_p$  and that the proton temperature  $T_p$  serves to modulate the efficiency of that mechanism. Table 3 also shows that  $E_{rms,2}$  has a significant negative correlation with the sound speed  $C_s$ , which is already implicit in the correlations with  $T_e/T_p$  and  $T_p$  if we note that  $C_s \propto [T_e + T_p]^{1/2} = [T_p(T_e/T_p + 1)]^{1/2}$ . It may also be observed that  $E_{rms,2}$  shows a negative correlation with  $V_{sw}$ , only marginal correlations with other parameters such as  $M_A$  and perhaps  $\beta$ , and no correlation with  $\psi(\mathbf{B}, \hat{n})$ .

In the column under  $E_{rms,1}$ , the rms electric field strength between 20 and 200 Hz, it can be seen that  $E_{rms,1}$  has its strongest correlation with  $T_e/T_p$ ; the corresponding points are plotted in Figure 9. A comparison of the correlation coefficients in Table 3 reveals that  $E_{rms,1}$  and  $E_{rms,2}$  have like correlations with  $T_e/T_p$ ,  $T_p$ , and  $C_s$ , i.e., with the same sign and ordering. However,  $E_{rms,1}$  also correlates with  $\psi(\mathbf{B}, \hat{n})$ , unlike  $E_{rms,2}$ , but instead like  $B_{rms}$ . The correlations of  $E_{rms,1}$  with  $T_e/T_p$ ,  $T_p$ ,  $C_s$ , and  $\psi(\mathbf{B}, \hat{n})$  thus indicate that the dependence of  $E_{rms,1}$  on the upstream parameters includes character-

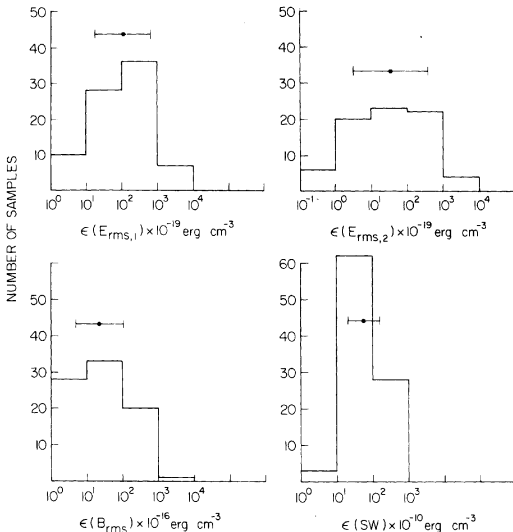


Fig. 6. The distributions of the absolute values of plasma wave energy densities and solar wind energy density.

TABLE 2. Energy Density Characteristics

	Min	Max	Mean*	Standard Deviations*	
				Minus	Plus
$\epsilon(E_{rms,1})/\epsilon(sw), \times 10^{-8}$	0.0028	6.4	0.17	0.021	1.3
$\epsilon(E_{rms,2})/\epsilon(sw), \times 10^{-8}$	0.0001	14.2	0.054	0.0047	0.63
$\epsilon(B_{rms})/\epsilon(sw), \times 10^{-6}$	0.026	5.9	0.38	0.10	1.4
$\epsilon(E_{rms,1}), \times 10^{-19} \text{ erg cm}^{-3}$	3.7	3020.	105.	16.	672.
$\epsilon(E_{rms,2}), \times 10^{-19} \text{ erg cm}^{-3}$	0.32	6120.	34.	2.9	400.
$\epsilon(B_{rms}), \times 10^{-16} \text{ erg cm}^{-3}$	1.1	2600.	24.	5.0	115.
$\epsilon(sw), \times 10^{-10} \text{ erg cm}^{-3}$	6.9	440.	59.	22.	161.

\*Logarithmic means and standard deviations.

TABLE 3. Correlation Coefficients  $R$  for  $\log y = bx + a$ 

$x$	$y = E_{rms,1}$ (20 Hz to 200 Hz)		$y = E_{rms,2}$ (200 Hz to 4 kHz)		$y = B_{rms}$ (20 Hz to 4 kHz)	
	$S = 81$ $R_c(1\%) =$ 0.281	$S = 96$ $R_c(1\%) =$ 0.259	$S = 75$ $R_c(1\%) =$ 0.292	$S = 90$ $R_c(1\%) =$ 0.267	$S = 82$ $R_c(1\%) =$ 0.280	$S = 98$ $R_c(1\%) =$ 0.257
$M_A$		-0.294		-0.300		0.149
$\beta$		-0.286		-0.266		0.150
$C_A$		0.286		0.136		-0.103
$\psi(B, \tilde{n})$		0.342		0.141		0.386
$ B $		0.306		0.165		0.342
$M_s$	0.186		0.236		0.131	
$T_e/T_p$	0.416		0.599		-0.110	
$V_{sw}$	-0.165		-0.361		0.300	
$C_s$	-0.328		-0.463		0.040	
$N$	0.032		0.242		0.500	
$T_e$	-0.200		-0.241		-0.117	
$T_p$	-0.376		-0.566		0.185	

Here  $M_A = V_{sw}/C_A$ ,  $M_s = V_{sw}/C_s$ ,  $\beta = 8\pi NK(T_e + T_p)/|B|^2$ ,  $C_A = |B|/(4\pi Nm_p)^{1/2}$ , and  $C_s = [k(K/m_p)(T_e + T_p)]^{1/2}$ .

istics of both purely electrostatic turbulence and purely electromagnetic turbulence. We may therefore conclude that in the low-frequency portion of the shock spectrum the electric field is derived from the fields of coupled electrostatic and electromagnetic waves. A similar conclusion was reached in paper 1, where it was shown that below about 200 Hz the ratio of electric field energy density to magnetic field energy density  $\epsilon_E/\epsilon_B$  is greater than that expected for whistler waves and that therefore the electric field energy density  $\epsilon_E$  must also include electrostatic waves. It can thus be seen that the entire shock electric field spectrum is primarily composed of electrostatic waves, which couple to whistlers at frequencies below the electron gyrofrequency. An electrostatic wave which can couple to whistlers in a high  $\beta$  plasma, such as the solar wind,

is the ion sound wave [Formisano and Kennel, 1969]. From the discussion of Formisano and Kennel [1969] it may be inferred that whistlers and ion sound waves can couple over a broad range of frequencies below the electron gyrofrequency whenever strong temperature gradients occur; this result is consistent with the observations of electrostatic and electromagnetic waves below about 200 Hz in the bow shock spectrum.

The observed correlations of  $E_{rms,1}$  and  $E_{rms,2}$  with  $T_e/T_p$  and  $T_p$  imply that the kinetic properties of the solar wind plasma, i.e., the wave-particle interactions that modify the electron and proton velocity distributions, are the primary factors determining the intensity of electrostatic turbulence in the bow shock. Usually  $T_e > T_p$  in the upstream region and leading edge of the shock. The observation of temperature jumps in  $T_e$  and  $T_p$  across the shock such that  $T_p$  is 2-4 times greater than  $T_e$  in the near downstream region means that protons provide the major dissipation mechanism for the bow shock [Montgomery et al., 1970]. The electric field spectrum from which  $E_{rms,1}$  and  $E_{rms,2}$  are computed can thus be associated with proton heating.

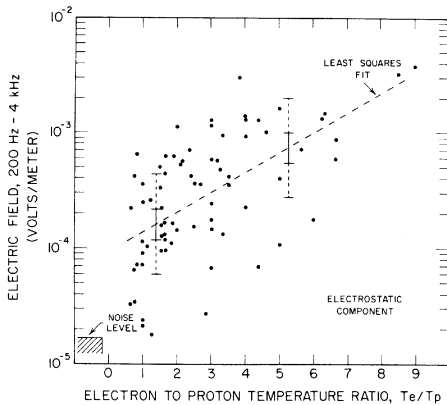


Fig. 7. Plot of  $E_{rms,2}$ , the rms field strength of the electrostatic component of the shock spectrum (200 Hz to 4 kHz), against  $T_e/T_p$ , showing a strong positive correlation. The dashed diagonal line is the line of regression for a least squares fit to the equation  $\log y = bx + a$ , where  $y = E_{rms,2}$  and  $x = T_e/T_p$ . The slope of the regression line, which is the important measure of association, has a dispersion which is indicated by rotating the regression line about its centroid to the limits indicated by the small error bars at  $\pm 2.576\sigma(y)$ . The large error bars at  $\pm \sigma(y)$  probably arise from short-period fluctuations in  $T_e/T_p$  and from correlations with other upstream parameters not considered in this two-parameter fit.

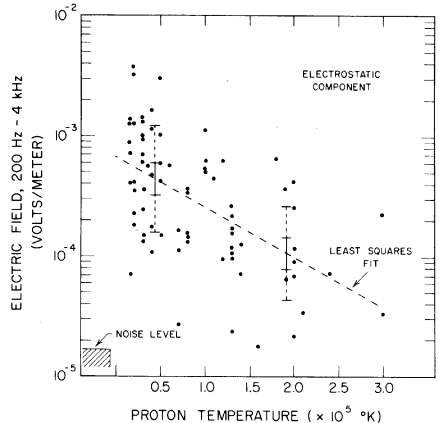


Fig. 8. Plot of  $E_{rms,2}$  against the upstream proton temperature  $T_p$ , showing a strong negative correlation for a least squares fit to  $\log y = bx + a$ , where  $y = E_{rms,2}$  and  $x = T_p$ . The error bars have the same meaning as in Figure 7.

Such fluid parameters as  $M_A$ ,  $\beta$ , and  $\psi(\mathbf{B}, \hat{n})$ , with which  $E_{rms,1}$  and  $E_{rms,2}$  have weak or null correlations, are apparently not important determinants of the intensity variations in the shock electric field spectrum. However, it should be noted that the MHD structure of the bow shock is often classified in terms of  $M_A$ ,  $\beta$ , and  $\psi(\mathbf{B}, \hat{n})$  [Formisano and Hedgecock, 1973a; Greenstadt, 1974], and within these classifications, almost all of the shocks used in the correlations of Table 3 fall into the category in which the bow shock is most often found, that of 'turbulent shocks' with  $M_A > 3$ ,  $\beta > 0.1$ , and  $\psi(\mathbf{B}, \hat{n}) \sim 30^\circ$ - $70^\circ$ . Certain critical values of the upstream fluid parameters,  $M_A^* \sim 2.5$ - $3.0$ ,  $\beta \sim 0.1$ , and  $\psi(\mathbf{B}, \hat{n}) = 88.7^\circ$ , at which significant changes in the MHD structure of collisionless shocks occur [Woods, 1969a, b, 1970; Paul, 1972; Tidman and Krall, 1971, chapter 3; Biskamp, 1973] are not well represented in the correlations of Table 3.

#### ELECTROMAGNETIC TURBULENCE

For the upstream parameters of Table 3, electromagnetic turbulence, represented by the magnetic field strength  $B_{rms}$ , is found to display a strong correlation with the particle density  $N$ . Figure 10 shows the plot of  $B_{rms}$  and  $N$ ; the line of regression and error bars have the same meaning as in previous figures. The slope of the regression line indicates that more intense magnetic field fluctuations occur for larger values of the particle density, a variation consistent with whistler waves, since the index of refraction ( $=cB/E$ ) for the whistler mode increases with particle density. The positive correlation between  $B_{rms}$  and  $N$  supports the previous conclusion that whistler waves comprise the shock magnetic field spectrum. The slope of the regression line in Figure 10 is not drastically changed if the relatively few points at high density are omitted from the fit.

The shock normal angle  $\psi(\mathbf{B}, \hat{n})$  is the only other parameter of Table 3 with which  $B_{rms}$  shows a substantially significant correlation. The plot of  $B_{rms}$  and  $\psi(\mathbf{B}, \hat{n})$  is shown in Figure 11. Here  $\psi(\mathbf{B}, \hat{n})$  takes values in the range  $0^\circ$ - $90^\circ$ , with  $\psi(\mathbf{B}, \hat{n}) = 0^\circ$  being defined as a parallel shock,  $0^\circ < \psi(\mathbf{B}, \hat{n}) \leq 88.7^\circ$  as an oblique shock, and  $88.7^\circ < \psi(\mathbf{B}, \hat{n}) \leq 90^\circ$  as a perpendicular shock. These definitions for  $\psi(\mathbf{B}, \hat{n})$  are theoretical [Tidman and Krall, 1971, p. 24]; the experimental values for shock normal angles have error limits of  $\pm(5^\circ$ - $10^\circ)$ , so that most shocks can be considered oblique,  $\psi(\mathbf{B}, \hat{n}) \sim 0^\circ$ - $85^\circ$ , or perpendicular,  $\psi(\mathbf{B}, \hat{n}) \sim 85^\circ$ - $90^\circ$ . Other classifications are also used [Greenstadt, 1974]. Whistlers propagate in a cone about the direction of  $\mathbf{B}$ ; therefore as  $\mathbf{B}$  lies closer to the plane of the shock, i.e., as  $\psi(\mathbf{B}, \hat{n}) \rightarrow 90^\circ$ , on the average it can be expected that the energy density of whistler waves in the plane of the shock will increase. Therefore the positive correlation of  $B_{rms}$  and  $\psi(\mathbf{B}, \hat{n})$  also supports the identification of  $B_{rms}$  as whistler turbulence.

The frequency range of  $B_{rms}$  (20 Hz to 4 kHz) corresponds to the high-frequency end of a much broader spectrum of magnetic field fluctuations of the bow shock region which generally has its largest spectral densities at frequencies near and below the proton gyrofrequency (0.001-1.0 Hz) [Holzer et al., 1966, 1972; Olson et al., 1969; Fairfield and Ness, 1970]. Since most of the magnetic field energy density is at the much lower frequencies associated with the MHD regime, it is not surprising that  $B_{rms}$  has insignificant correlations with MHD fluid parameters such as  $M_A$  and  $\beta$ .

A positive correlation between  $B_{rms}$  and the upstream magnetic field magnitude  $|\mathbf{B}|$  is also indicated in Table 3. The observed correlation is not related to the shift of the whistler

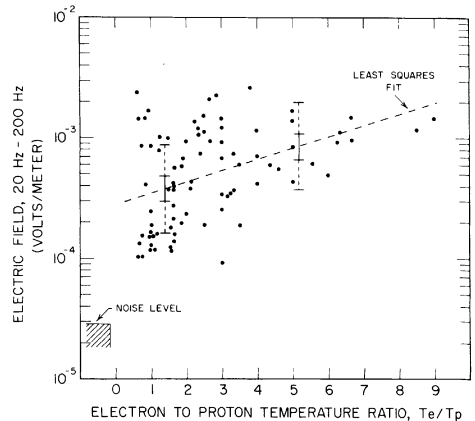


Fig. 9. Plot of  $E_{rms,1}$  against  $T_e/T_p$ , which indicates a positive correlation. The correlation between  $E_{rms,1}$ , which is the rms field strength of the electric field between 20 and 200 Hz in the shock spectrum, and  $T_e/T_p$  is observed to be similar to that between  $E_{rms,2}$  and  $T_e/T_p$ , shown in Figure 7. The error bars have the same meaning as in the two previous figures.

cutoff, i.e., the electron gyrofrequency, toward a higher frequency in the spectrum of magnetic field fluctuations, since for a typical spectrum that varies as  $f^{-4}$  the largest expected upward shift in the whistler cutoff increases  $B_{rms}$  by only about 1%, whereas the values observed for  $B_{rms}$  range over more than an order of magnitude. The correlation of  $B_{rms}$  with  $|\mathbf{B}|$  thus indicates an actual statistical increase in the intensity of magnetic field fluctuations with an increase in  $|\mathbf{B}|$ . The correlation appears to be weak, however.

#### BOW SHOCK STRUCTURE

The leading edge of a collisionless plasma shock wave has been considered in theoretical studies to be a region where particle reflection and heating can occur, which greatly influence the dissipation processes further into the shock [Woods, 1969b, 1971; Biskamp, 1970, 1973; Biskamp and Welter, 1972;

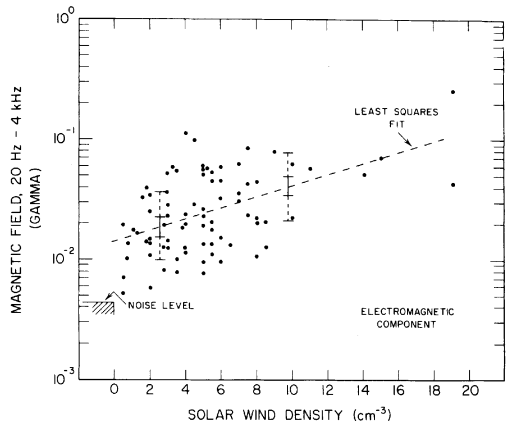


Fig. 10. Plot of  $B_{rms}$ , the rms magnetic field strength of the electromagnetic component of the shock spectrum (20 Hz to 4 kHz), against the solar wind particle density  $N$ . A positive correlation is indicated. The error bars have the same meaning as in the three previous figures.

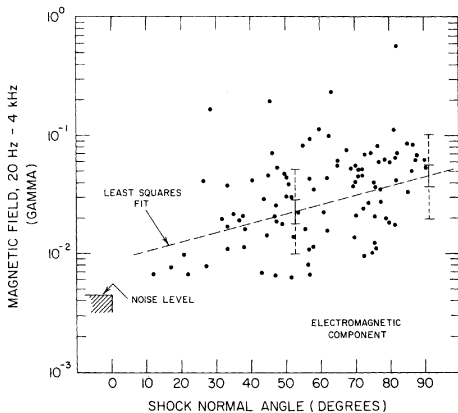


Fig. 11. Plot of  $B_{rms}$  against the shock normal angle  $\psi(\mathbf{B}, \hat{n})$ , showing a positive correlation. The error bars have the same meaning as in the four previous figures.

*Tidman and Krall*, 1971, p. 130]. Experimental measurements of electron and ion velocity distributions near the earth's bow shock have shown that electron preheating and ion deceleration do occur near the foot of the magnetic field gradient [*Montgomery et al.*, 1970; *Neugebauer*, 1970; *Neugebauer et al.*, 1971]. The leading edge and transition region of the bow shock can often be resolved in the structure of the plasma wave spectra that are obtained at a given shock crossing. It may therefore be expected that electron preheating should result in a broad spectrum of turbulent electrostatic waves at the leading edge of the bow shock. In fact, electrostatic waves are typically observed on the upstream side of the transition region in almost all bow shock crossings that we have studied. In the main transition region of the shock the spectrum of plasma waves is modified significantly and can be associated with the ion thermalization that provides the major dissipation for the shock [*Montgomery et al.*, 1970].

The data in Figure 12 were obtained for a perpendicular shock in which the transition region is clearly defined. The top panel shows the electric field in the 3.11-kHz channel of the University of Iowa spectrum analyzer which was measured with the rapid-sample mode described in paper 1. The magnetic field measured by the GSFC magnetometer is shown in the lower panel. The angles  $\phi_B$  and  $\theta_B$  are the solar ecliptic longitude and latitude of  $\mathbf{B}$ . Before about 14h 40m 38s UT the spacecraft is in the quiet upstream solar wind. At 14h 40m 38s UT the leading edge of the bow shock is encountered as shown by the sudden increase in electric field strength above the solar wind noise level and the corresponding onset of fluctuations in the magnetic field. It can be seen that the electric field increases substantially in the time interval between the vertical dashed lines labeled A and B, before the main gradient of the magnetic field, which occurs in the time interval between vertical dashed lines labeled B and C. Since the spectrum of electron plasma oscillations (peaked at about  $f_{pe} \sim 30$  kHz) is often observed to broaden toward 3.11 kHz upstream of the bow shock, the electrostatic noise between points A and B in Figure 12 may indicate a heating of the solar wind electron distribution just before the main gradient of the magnetic field occurs. Such preheating of electrons would substantially increase the value of  $T_e/T_p$  in the leading edge of the shock with a consequent lowering of the threshold for the destabilization of drift cur-

rents such as occur with ion sound waves [*Tidman and Krall*, 1971, p. 128]. The electrostatic turbulence between B and C correlates well with the magnetic field gradient, similar to the results of *Fredricks et al.* [1968, 1970b]. It can be expected that most of the ion thermalization must occur in the region of this large gradient [*Montgomery et al.*, 1970; *Greenstadt et al.*, 1975]. It is clear that in the shock crossing of Figure 12 the structure of electrostatic turbulence in the leading edge of the shock is not greatly different from that in the main transition, this similarity indicating that the regions of electron and ion heating overlap. In the immediate downstream region the electric field noise intensity at 3.11 kHz shows a series of nearly periodic fluctuations that display exponentially decreasing magnitude. The periodicity of the larger downstream fluctuations is not related to the spacecraft spin period, so it may be assumed that the fluctuations are real time variations of electrostatic turbulence. The exponential envelope of the downstream fluctuations implies that the spectrum of electrostatic waves is being damped, perhaps by the type of fluctuations in the ion distribution observed by *Montgomery et al.* [1970] in the downstream region.

A second example of a perpendicular shock in which the structure of the transition region is clearly defined is shown in Figure 13. The top panel shows the electric field in four channels (36 Hz, 311 Hz, 3.11 kHz, 31.1 kHz) of the plasma wave spectrum analyzer, the vertical bars indicating average measurements and the dots indicating peak measurements. The magnitude and direction angles of the magnetic field measured simultaneously by the GSFC magnetometer are shown in the bottom panel. A vertical dashed line at about 22h 19m 00s UT marks the time at which the shock transition region begins as determined by the electric field measurements. It can be seen that the electric field noise begins almost 1 min before the main gradient of the magnetic field. The shock transition region is fairly wide in time, and the 5.12-s average measurements can resolve the changes in the electric field spectrum as the transition region is traversed. The beginning of the transition region is detected simultaneously in all channels; however, the rise times to maximum electric field intensity in the transition region are progressively shorter for increasing frequency. The relaxation from maximum intensity in the two high-frequency channels begins before the maximum intensity is reached in the two low-frequency channels, so that by the time the maximum field strength occurs at 311 Hz, the electric field intensity at 31.1 kHz is nearly back to the noise level. The magnetic field measurements indicate that the electrostatic turbulence at lower frequencies correlates with the main transition region, while the electrostatic turbulence at high frequencies correlates with the leading edge of the bow shock.

Between 22h 19m 20s and 22h 20m 00s UT, when the spacecraft was in the leading edge of the shock transition, a rapid-sample measurement of the 31.1-kHz electric field channel occurred. The rapid-sample data are shown in the polar plot of Figure 14, in which the electric field measurements are plotted versus the spin angle of the spacecraft antenna in the solar ecliptic plane. During the time of the rapid-sample measurements the average magnetic field direction in the leading edge of the bow shock had a solar ecliptic latitude  $\theta_B \sim 30^\circ$  and a solar ecliptic longitude  $\phi_B \sim 90^\circ$ . The projection of the magnetic field vector into the solar ecliptic plane at  $\phi_B \sim 90^\circ$  is indicated in the polar plot of Figure 14. By computing the second moments of the rapid-sample measurements about the solar ecliptic  $x$  and  $y$  axes (equivalent to evaluating the moments of inertia for unit 'mass' particles with moment arms



equal to the fluctuation amplitudes) and diagonalizing the resulting matrix the principal axes may be obtained for the two-dimensional distribution of rapid-sample measurements. The direction of the minor principal axis, indicated by  $\phi_p$  on the polar plot, represents the average polarization direction of the electric field fluctuations. It is evident that the average electric field polarization is nearly aligned with the magnetic field vector direction ( $\phi_B - \phi_p \sim 10^\circ$ ); the frequency and average polarization therefore identify the noise as electron plasma oscillations [Fredricks *et al.*, 1968, 1970b; Rodriguez and Gurnett, 1975]. The spectrum of electron plasma oscillations at about 22h 19m 00s UT (20 s before the rapid-sample data of Figure 14 were obtained) is sharply peaked at the electron plasma frequency near 16.5 kHz. The broadening of the spectrum of electron plasma oscillations toward the higher frequency 31.1 kHz indicates that heating of the electron distribution began just before the rapid-sample measurement was taken and occurs throughout the rapid-sample time interval. The five consecutive average electric field spectra measured between 22h 20m 00s and 22h 20m 26s UT immediately after the rapid-sample measurement of the 31.1-kHz channel and corresponding with the main gradient of the magnetic field (see Figure 13) are shown in the bottom panel of Figure 14. Each spectrum is labeled by a time-ordered snapshot number. The averaging time of snapshot 1 includes the foot of the magnetic field gradient. Snapshot 5 is the most intense electric field spectrum of the sequence and is defined as the shock electric field spectrum, similar to the spectra shown in Figure 1. The development of the broad peak centered near the 3.11-kHz channel in snapshot 1 correlates with the appearance, in the leading edge of the shock, of 0.5- to 4.0-Hz whistler waves of the type reported by Fairfield [1974]. Further upstream, where the spectrum of electron plasma oscillations is sharply peaked at the electron plasma frequency near 16.5 kHz, the 0.5- to 4.0-Hz waves have damped out. These upstream whistler waves probably involve resonant interactions with electrons [Fairfield, 1974]. Therefore the broadening of the spectrum of electron plasma oscillations toward lower frequencies probably indicates scattering interactions between upstream electrons and the 0.5- to 4.0-Hz whistler waves. The overall broadening of the spectrum of electron plasma oscillations toward 31.1 and 3.11 kHz thus clearly indicates the occurrence of electron heating in the leading edge of the shock, and we interpret the peak at 3.11 kHz in snapshot 1 to mean that maximum heating of the electron distribution has occurred.

Following the sequence of snapshot numbers 1-5, it can be seen that as the main gradient of the magnetic field of the shock is traversed the electric field spectrum develops a peak at 3.11 kHz. Since proton heating in the bow shock is observed to occur after electron heating [Montgomery *et al.*, 1970; Formisano and Hedgecock, 1973b], i.e., deeper within the shock transition region, we therefore conclude that the broad peak centered at 311 Hz in the shock spectrum corresponds to the occurrence of maximum proton heating. This broad peak of electrostatic turbulence in the shock spectrum is usually centered between 200 and 800 Hz, corresponds to  $E_{rms,2}$  in the correlations of Table 3, and is characteristic of almost all shock crossings, as shown by the sample of shock spectra in Figure 1. Also characteristic of most bow shock crossings is the sequential development in electric field spectra through the shock transition shown by snapshots 1-5 of Figure 14, which suggests that the electrostatic turbulence associated with the

3.11 kHz peak couples into lower frequencies during the proton heating process. It is interesting to note that this variation in electrostatic turbulence with frequency indicates that a strong coupling mechanism exists between the electron and proton heating processes in the bow shock, since the direction of energy cascade in the spectrum of electrostatic turbulence is toward lower frequencies rather than toward higher frequencies as might be expected [Roth, 1971] in a turbulent spectrum analogous to conventional hydrodynamic turbulence. Past the downstream edge of the transition region the top panel of Figure 13 shows that the electrostatic turbulence at low frequencies decreases but still remains at an intensity that is large in comparison with the noise at higher frequencies. The resulting electric field spectrum in the near downstream region resembles the shock spectrum at a reduced intensity.

It can also be seen in Figure 13 that in the upstream region before about 2213 UT the GSFC magnetometer data show the

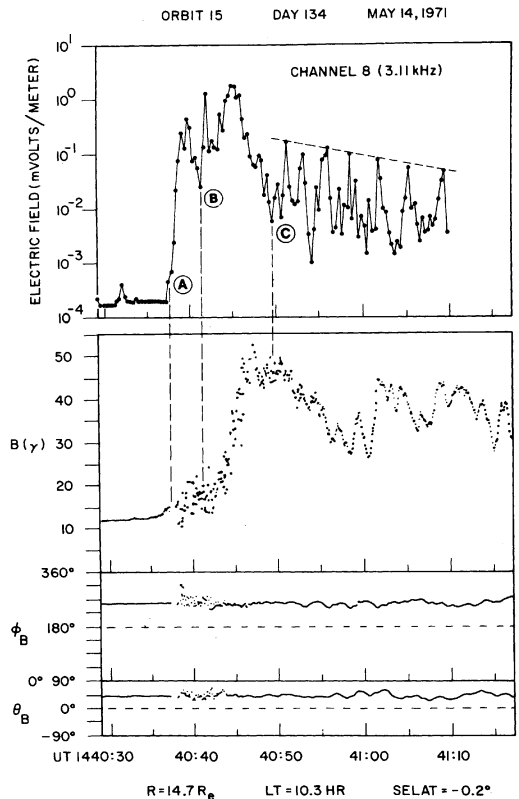


Fig. 12. Rapid-sample measurement of the electric field at 3.11 kHz showing the correlation with the transition region as determined by the magnetic field. The interval between the vertical dashed lines labeled A and B indicates the leading edge of the shock where the initial electrostatic noise occurs. The main transition region, between B and C, corresponds to the large gradient in the magnetic field and the associated electrostatic turbulence. The intervals A-B and B-C probably correspond to the regions of maximum electron and proton heating, respectively. Downstream fluctuations in electrostatic noise display an exponential damping which may result from further proton heating. The apparent periodicity of the major downstream fluctuations is not related to the spacecraft spin period, so it may be assumed that the fluctuations are real time variations. Shock parameters are  $M_A = 4.8$ ,  $\beta = 0.28$ ,  $T_e/T_p = 6.7$ , and  $\psi(B, \bar{n}) = 87^\circ$ .

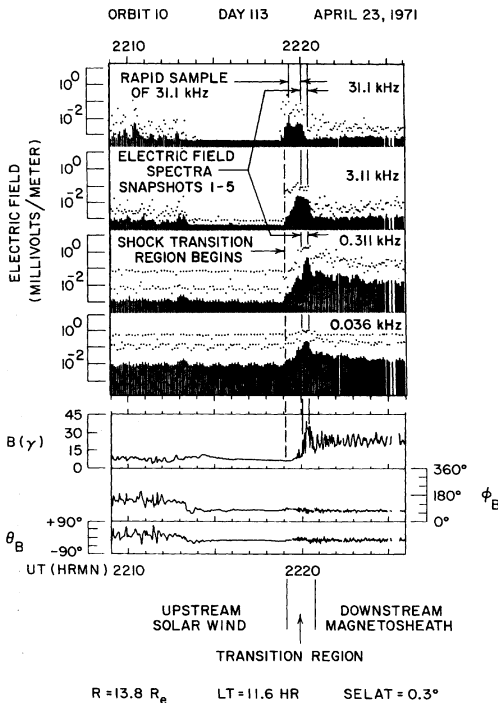


Fig. 13. A shock crossing which shows the relation between the rise and relaxation times of electric field turbulence at high and low frequencies. Electric field noise is clearly detected ahead of the main gradient in the magnetic field. The solid vertical lines indicate the time intervals for the rapid-sample measurement and electric field spectra of Figure 14. Upstream electrostatic oscillations at 3.11 and 31.1 kHz are correlated with the long-period waves in the magnetic field. Shock parameters are  $M_A = 6.9$ ,  $\beta = 1.42$ ,  $T_e/T_p = 1.0$ , and  $\psi(B, \hat{n}) = 90^\circ$ .

presence of long-period (3–60 s) waves of the type which is thought to be generated by superthermal proton streams reflected from the bow shock [Greenstadt *et al.*, 1968, 1970; Fairfield, 1969; Barnes, 1970; Scarf *et al.*, 1970; Fredricks, 1975]. Scarf *et al.* [1970] have observed direct correlations between electrostatic oscillations at 3 kHz, associated with the ion plasma frequency in the solar wind, and the long-period magnetic field oscillations. The top panel of Figure 13 shows that electrostatic oscillations at 31.1 kHz, associated with the electron plasma frequency, are also in direct correlation with the long-period waves in the interplanetary magnetic field. The electrostatic oscillations at 31.1 kHz probably result from the electron stream that must accompany the reflected proton stream to provide charge neutralization.

#### SUMMARY OF RESULTS AND CONCLUSIONS

The plasma wave turbulence of the earth's bow shock displays distinct correlations with several upstream solar wind parameters. It is found that the intensity variations of electrostatic turbulence in the bow shock correlate strongly with the ratio of electron to proton temperatures  $T_e/T_p$  and with the proton temperature  $T_p$ , as measured in the upstream solar wind. For large values of  $T_e/T_p$ , large values of the electrostatic rms field strength  $E_{rms,2}$  occur, where  $E_{rms,2}$  is obtained by integrating the shock electric field spectrum from 200 Hz to 4 kHz. The negative correlation found between  $E_{rms,2}$

and  $T_p$  implies that changes in the upstream proton temperature modulate the efficiency of the electrostatic turbulence mechanism which is associated with the value of  $T_e/T_p$ . If we make the plausible assumption that more intense levels of electrostatic turbulence occur when an unstable plasma is further removed from the threshold of stability, then we can relate the observed correlations of  $E_{rms,2}$  with  $T_e/T_p$  and  $T_p$  to specific electrostatic wave modes whose stability criteria depend on  $T_e/T_p$  and  $T_p$ . Two-stream instability criteria are often expressed in terms of the two parameters  $T_e/T_i$  and  $v_d/v_e$ , where  $v_d$  is a relative drift velocity and  $v_e$  is the electron thermal speed [Stringer, 1964; Tidman and Krall, 1971, chapter 7]. A discussion of two-stream instability modes that are candidates for bow shock turbulent heating mechanisms has been given by Greenstadt and Fredricks [1974], who derive stability criteria in terms of the minimum relative drift speed  $v_d$  between electrons and ions which must be exceeded over the

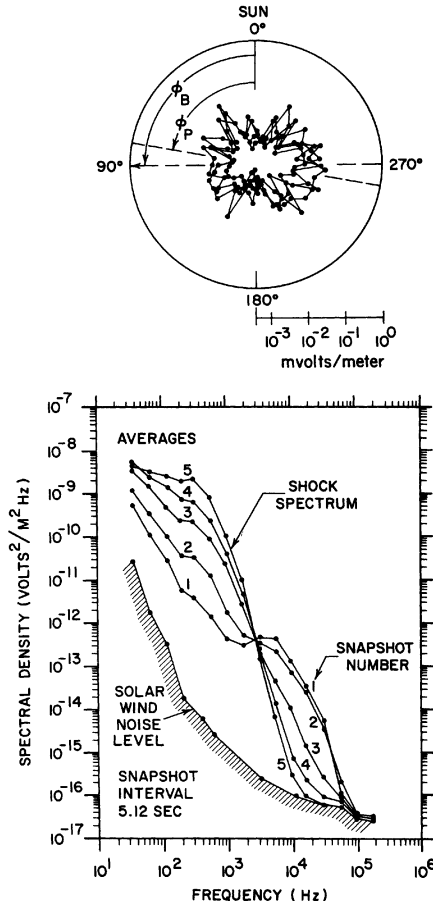


Fig. 14. The polar plot is a rapid-sample measurement plotted versus the spacecraft spin angle in the solar ecliptic plane and represents the electrostatic turbulence at 31.1 kHz in the leading edge of the shock crossing in Figure 13. The orientation of the upstream magnetic field vector is indicated by  $\phi_B$ . The minor principal axis of the distribution of rapid-sample measurements is indicated by  $\phi_P$ . The electric field spectra in the bottom panel indicate the sequential development of electrostatic turbulence with frequency as the main transition is traversed.

scale length of the shock magnetic field gradient  $\Delta B/B_0$  in order for instability to occur. Various scale lengths are chosen, all of which are proportional to  $T_e/T_i$  and/or  $\beta_i$  ( $=8\pi NKT_i/|B|^2$ ). The temperature ratio  $T_e/T_i$  and the relative drift velocity  $v_d$  (or  $v_d/v_e$ ) indicate the relative widths of the electron and ion distribution functions and the relative displacement between the maximums of the two distributions, respectively. In terms of  $T_e/T_i$  and  $v_d$  the two-stream stability criteria indicate how well resolved from each other in velocity space the two streams have to be before unstable waves are generated. In general, anything that increases the resolution between the streams enhances the potential for instability and would be expected to lead to more intense levels of electrostatic turbulence. In particular, the positive correlation between  $E_{rms,2}$  and  $T_e/T_p$  suggests that electrostatic turbulence in the bow shock is associated with a two-stream instability, the stability threshold of which is probably exceeded if  $T_e$  increases substantially in the leading edge of the bow shock. Electron preheating in the leading edge is confirmed by the broadening of the spectrum of electron plasma oscillations over the range of frequencies 3–30 kHz. For typical solar wind conditions, only the electron distribution undergoes an appreciable drift in the bow shock gradient [Wu and Fredricks, 1972], so that the instability arises from electrons drifting through an ion background. The result of this study that  $E_{rms,2}$  has a strong negative correlation with the proton temperature  $T_p$  is consistent with an electron-proton streaming instability, because for a given relative displacement  $v_d/v_e$  a smaller width for the proton distribution  $f_p(v)$  contributes to better resolution of the two streams and an enhanced potential for instability. Thus variations in  $T_p$  could serve to modulate the intensity of the resulting electrostatic turbulence.

As was indicated by Greenstadt and Fredricks [1974], streaming between electron and proton distributions preferentially heats electrons, a result that corresponds to the observation that maximum electron heating occurs in the leading edge of the bow shock. To heat ions, the major dissipation mechanism of the bow shock, to temperatures such that  $T_p \sim (2-4)T_e$  requires a streaming between ions [Auer et al., 1971; Papadopoulos, 1971; Biskamp and Welter, 1972] or other nonlinear instability modes. In the correlations of Table 3,  $E_{rms,2}$  corresponds to the electrostatic turbulence observed in the main shock gradient and was identified with the maximum heating of protons. The strong correlation of  $E_{rms,2}$  with  $T_e/T_p$  and  $T_p$  as measured upstream of the bow shock thus implies that the heating of protons in the main transition is strongly coupled to the heating of electrons in the leading edge of the shock. The coupling of the electron and proton heating mechanisms is most clearly shown by the characteristic sequential development of the electric field spectrum through the shock transition, an example of which is shown in Figure 14, in which the intensity of electrostatic turbulence at lower frequencies ( $\sim 300$  Hz) increases simultaneously with a decrease in electrostatic turbulence at the higher frequencies associated with electron preheating. The low-frequency (200–800 Hz) peak in the spectrum of electrostatic turbulence, associated with the maximum in proton heating, is characteristic of almost all shock electric field spectra.

Low-frequency (20–200 Hz) electric field turbulence, represented by  $E_{rms,1}$ , is found to correlate strongly with  $T_e/T_p$  and  $T_p$ , similar to the correlations of  $E_{rms,2}$  with  $T_e/T_p$  and  $T_p$ , and therefore indicates that a substantial portion of the electric field energy density at low frequencies is derived from electrostatic waves. The entire electric field spectrum measured in

the bow shock is thus primarily composed of electrostatic turbulence and is associated with the occurrence of maximum proton heating. Since  $E_{rms,1}$  also correlates with the shock normal angle  $\psi(\mathbf{B}, \hat{n})$ , similar to the correlation of  $B_{rms}$  with  $\psi(\mathbf{B}, \hat{n})$ , this is taken as evidence that  $E_{rms,1}$  is also derived from the electric field of an electromagnetic mode, probably whistlers, which couples to electrostatic waves at frequencies below the electron gyrofrequency.

Electromagnetic turbulence in the bow shock, represented by the rms field strength of magnetic field fluctuations  $B_{rms}$  in the range 20 Hz to 4 kHz, is found to show positive correlations with the particle density  $N$  and the shock normal angle  $\psi(\mathbf{B}, \hat{n})$ . These correlations are consistent with whistler turbulence with high density, perpendicular shocks having the largest values of  $B_{rms}$ . Upstream fluid parameters, such as  $M_A$  and  $\beta$ , used in the MHD description of the bow shock, do not correlate with  $B_{rms}$ , presumably because the range of frequencies for  $B_{rms}$  covers only the high-frequency low-spectral density portion of the total magnetic field spectrum near the bow shock.

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#### REFERENCES

- Auer, P. L., R. W. Kilb, and W. F. Crevier, Thermalization in the earth's bow shock, *J. Geophys. Res.*, **76**, 2927, 1971.
- Barnes, A., Theory of generation of bow-shock-associated hydro-magnetic waves in the upstream interplanetary medium, *Cosmic Electrodynamics*, **1**, 90, 1970.
- Bevington, P. R., *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill, New York, 1969.
- Biskamp, D., Ion sound turbulence in a collisionless shock wave, *J. Geophys. Res.*, **75**, 4659, 1970.
- Biskamp, D., Collisionless shock waves in plasmas, *Nucl. Fusion*, **13**, 719, 1973.
- Biskamp, D., and H. Welter, Structure of the earth's bow shock, *J. Geophys. Res.*, **77**, 6052, 1972.
- Fairfield, D. H., Bow shock associated waves observed in the far upstream interplanetary medium, *J. Geophys. Res.*, **74**, 3541, 1969.
- Fairfield, D. H., Average and unusual locations of the earth's magnetopause and bow shock, *J. Geophys. Res.*, **76**, 6700, 1971.
- Fairfield, D. H., Whistler waves observed upstream from collisionless shocks, *J. Geophys. Res.*, **79**, 1368, 1974.
- Fairfield, D. H., and N. F. Ness, Magnetic field fluctuations in the earth's magnetosheath, *J. Geophys. Res.*, **75**, 6050, 1970.
- Formisano, V., and P. C. Hedgecock, Solar wind interaction with the earth's magnetic field, 3, On the earth's bow shock structure, *J. Geophys. Res.*, **78**, 3745, 1973a.
- Formisano, V., and P. C. Hedgecock, On the structure of the turbulent bow shock, *J. Geophys. Res.*, **78**, 6522, 1973b.
- Formisano, V., and C. F. Kennel, Small amplitude waves in high  $\beta$  plasmas, *J. Plasma Phys.*, **3**, 55, 1969.
- Formisano, V., and G. Moreno, Relationships among the interplanetary plasma parameters: Heos 1, December 1968 to December 1969, *J. Geophys. Res.*, **79**, 5109, 1974.
- Fredricks, R. W., A model for generation of bow-shock-associated upstream waves, *J. Geophys. Res.*, **80**, 7, 1975.
- Fredricks, R. W., C. F. Kennel, F. L. Scarf, G. M. Crook, and I. M. Green, Detection of electric-field turbulence in the earth's bow shock, *Phys. Rev. Lett.*, **21**, 1761, 1968.
- Fredricks, R. W., F. V. Coroniti, C. F. Kennel, and F. L. Scarf, Fast time-resolved spectra of electrostatic turbulence in the earth's bow shock, *Phys. Rev. Lett.*, **24**, 994, 1970a.
- Fredricks, R. W., G. M. Crook, C. F. Kennel, I. M. Green, and F. L. Scarf, Ogo 5 observations of electrostatic turbulence in bow shock magnetic structures, *J. Geophys. Res.*, **75**, 3751, 1970b.

- Greenstadt, E. W., Structure of the terrestrial bow shock, in *Solar Wind Three*, edited by C. T. Russell, p. 440, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, 1974.
- Greenstadt, E. W., and R. W. Fredricks, Plasma instability modes related to the earth's bow shock, in *Magnetospheric Physics*, edited by B. M. McCormac, p. 355, D. Reidel, Dordrecht, Netherlands, 1974.
- Greenstadt, E. W., I. M. Green, G. T. Inouye, A. J. Hundhausen, S. J. Bame, and I. B. Strong, Correlated magnetic field and plasma observations of the earth's bow shock, *J. Geophys. Res.*, **73**, 51, 1968.
- Greenstadt, E. W., I. M. Green, G. T. Inouye, D. S. Colburn, J. H. Binsack, and E. F. Lyon, Dual satellite observation of the earth's bow shock, 2, Field-aligned upstream waves, *Cosmic Electrodynamics*, **1**, 279, 1970.
- Greenstadt, E. W., C. T. Russell, F. L. Scarf, V. Formisano, and M. Neugebauer, Structure of the quasi-perpendicular laminar bow shock, *J. Geophys. Res.*, **80**, 502, 1975.
- Holzer, R. E., M. G. McLeod, and E. J. Smith, Preliminary results from the Ogo 1 search coil magnetometer: Boundary positions and magnetic noise spectra, *J. Geophys. Res.*, **71**, 1481, 1966.
- Holzer, R. E., T. G. Northrop, J. V. Olson, and C. T. Russell, Study of waves in the earth's bow shock, *J. Geophys. Res.*, **77**, 2264, 1972.
- Montgomery, M. D., J. R. Asbridge, and S. J. Bame, Vela 4 plasma observation near the earth's bow shock, *J. Geophys. Res.*, **75**, 1217, 1970.
- Neugebauer, M., Initial deceleration of solar wind positive ions in the earth's bow shock, *J. Geophys. Res.*, **75**, 717, 1970.
- Neugebauer, M., C. T. Russell, and J. V. Olson, Correlated observations of electrons and magnetic fields at the earth's bow shock, *J. Geophys. Res.*, **76**, 4366, 1971.
- Neville, A. M., and J. B. Kennedy, *Basic Statistical Methods*, International Textbooks, Scranton, Pa., 1964.
- Olson, J. V., R. E. Holzer, and E. J. Smith, High-frequency magnetic fluctuations associated with the earth's bow shock, *J. Geophys. Res.*, **74**, 4601, 1969.
- Papadopoulos, K., Ion thermalization in the earth's bow shock, *J. Geophys. Res.*, **76**, 3806, 1971.
- Paul, J. W. M., Collisionless shocks, in *Cosmic Plasma Physics*, edited by K. Schindler, p. 293, Plenum, New York, 1972.
- Rodriguez, P., and D. A. Gurnett, Electrostatic and electromagnetic turbulence associated with the earth's bow shock, *J. Geophys. Res.*, **80**, 19, 1975.
- Roth, J. R., Experimental study of spectral index, mode coupling, and energy cascading in a turbulent, hot-ion plasma, *Phys. Fluids*, **14**, 2193, 1971.
- Scarf, F. L., R. W. Fredricks, L. A. Frank, C. T. Russell, P. J. Coleman, Jr., and M. Neugebauer, Direct correlations of large-amplitude waves with suprathermal protons in the upstream solar wind, *J. Geophys. Res.*, **75**, 7316, 1970.
- Stringer, T. E., Electrostatic instabilities in current-carrying and counterstreaming plasmas, *Plasma Phys.*, **C6**, 267, 1964.
- Tidman, D. A., and N. A. Krall, *Shock Waves in Collisionless Plasmas*, Interscience, New York, 1971.
- Woods, L. C., Critical Alfvén-Mach numbers for transverse field MHD shocks, *Plasma Phys.*, **11**, 25, 1969a.
- Woods, L. C., On the structure of collisionless magneto-plasma shock waves of super-critical Alfvén-Mach numbers, *J. Plasma Phys.*, **3**, 435, 1969b.
- Woods, L. C., On double-structured, perpendicular magneto-plasma shock waves, *Plasma Phys.*, **13**, 289, 1971.
- Wu, C. S., and R. W. Fredricks, Cyclotron drift instability in the bow shock, *J. Geophys. Res.*, **77**, 5585, 1972.

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