MAGNETIC AND ELECTRIC FIELD CHANGES ACROSS
THE SHOCK AND IN THE MAGNETOSHEATH

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1. Introduction

In recent months correlated measurements from the OGO-5 particle, field and wave
experiments have been used to study in detail the microscopic structure of the earth's
bow shock. As described in a series of preliminary reports [1, 2, 3, 4], instabilities
driven by currents at steep magnetic field gradients generally produce large amplitude
electrostatic waves. The electrostatic turbulence then interacts strongly with the
plasma particles, and this provides a primary shock dissipation mechanism.

Here we summarize the bow shock observations briefly, and we then consider a
number of closely related topics. Some intercorrelated spacecraft observations of
solar events are discussed using Pioneer 8 and OGO-5 data from March 14 and April
5, 1968. It is also shown that the two-stream current instability can be triggered by
strong magnetic field compressions that are not directly associated with the bow shock.
Field configurations that yield intense VLF electrostatic turbulence include those
near 'null regions' (probably associated with reconnection) and those associated with
large amplitude oblique magnetosonic waves.

2. Bow Shock Structure

The most commonly observed form of bow shock is one in which large amplitude
electrostatic waves provide a large share of the proton dissipation over short distances.
Figure 1 shows the magnetic field profile for a typical shock crossing of this type. As
described on the figure, a fairly well-defined sequence of changes in particle and wave
characteristics goes along with the variation in $|B|$. On the upstream side, the JPL
plasma probe measurements reveal that the positive ions first begin to slow down (in
this case near 2248:40), and shortly thereafter the Lockheed spectrometer generally
shows an abrupt increase in the proton thermal energy. For Figure 1, the largest
change in the proton 'temperature' is found to occur near 2248:43 to 2248:44, where
the TRW dipoles detect the peak electrostatic noise ($f \approx 500$ Hz to about 2 kHz). We
note that in almost all cases the JPL-UCLA search coil does detect some moderate
low frequency noise (the TRW loop at 560 Hz usually remains at its background value
throughout), and that some additional proton heating occurs over much longer
distances in the downstream region. However, for this type of 'electrostatic shock' it
appears that the major positive ion dissipation is provided by the interaction of the

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particles with electrostatic waves. It is also found that the peak $E$-field amplitudes are detected near the steepest gradients in $|\mathbf{B}|$, and it seems that the scale length of the strongest interaction may be as small as 2–5 km in the shock frame.

Some interpretations of these observations have been formulated [1, 2, 3, 4], and Figure 2 illustrates a probable sequence of events. A strong field gradient at the shock is produced by formation of a solitary pulse, by non-linear growth of a standing whistler mode wave to a large amplitude, or by some other, as yet unidentified, mechanism. At any rate, as the plasma flows into this region, we may consider that the initial sequence of events resembles the formation of an idealized Chapman-Ferraro sheath. The $\mathbf{V} \times \mathbf{B}$ forces produce a charge separation (dc) electric field that tends to slow down the positive ions. The electrons acquire additional energy, and a current system is naturally set up to maintain the gradient in $|\mathbf{B}|$. The thickness of this sheath region is about $(1–2) c/\omega_{pe}$, where $c$ is the speed of light and $\omega_{pe}/2\pi = 9 \times 10^3 (N)^{1/2}$ Hz is the electron plasma frequency. For nominal solar wind densities, the collisionless electron inertial length $\delta (\sim c/\omega_{pe})$ is about 2–4 km, in agreement with many observations.
Electrostatic waves develop in this region because the current is large enough to trigger a two-stream instability [1], and it appears that the oscillations are ion sound waves having $\mathbf{k}$ aligned with $\mathbf{j}$. For the shock crossing of Figure 1, the $E$-field spatial distribution is, in fact, confined to the region where one would expect strong currents on the basis of $(\mathbf{V} \times \mathbf{B})$. However, it must be realized that the actual instability is only described in a very general sense by this model. Recent high speed and high resolution measurements of the electron distribution functions on Vela 4 and 5 strongly suggest that resonant wave-particle interactions develop within the shock [5]. The ‘flat top’ electron distribution is indeed unstable with respect to ion acoustic waves, but the instability is somewhat more complex than the one suggested in the early discussions [1, 2].

3. The Bow Shock during a Storm

The VLF electric field experiments on Pioneer 8 and 9 allow us to explore the development of electrostatic noise in deep space when low Mach number interplanetary shocks are encountered [6, 7], and in several cases we can examine the changes in the bow shock region as the disturbed solar wind arrives at the earth. The lower part of Figure 3 shows the Pioneer 8 response in the (qualitative) broadband $E$-field channel for the period 13 March 1968 through 8 April 1968. At the beginning of this solar rotation (1842) the Pioneer 8 solar ecliptic coordinates were $X_{SE} = -1145 \, R_e$, $Y_{SE} = 1172 \, R_e$, and on April 8 we had $X_{SE} = -1356 \, R_e$, $Y_{SE} = 2155 \, R_e$, respectively. The Pioneer data displayed here represent maximum and minimum potential amplitudes in hourly samples, and the solid and open triangles show where prominent SC or SI events were detected on the ground.
The ground sudden commencement at 1328 UT on April 5 is clearly related to the enhanced noise signals detected on Pioneer 8, as shown by the heavy vertical arrow. Moreover, when this interplanetary shock front reached 1 AU, OGO-5 was in the outer magnetosheath and the storm encounter pushed the bow shock past the OGO, so that the spacecraft suddenly found itself in the solar wind. The upper part of Figure 3 shows the magnetic field profile, the $E$-field amplitudes in the 15% bandpass channels, and the $E$-field dynamic spectrum (the latter extends from 1 kHz to 22 kHz, and the closely-spaced, nearly horizontal lines below about 1 kHz represent the Rubidium magnetometer lines for this period). The high resolution capabilities of the OGO-5 instrumentation (8 kilobits/sec digital data rate plus broadband telemetry) thus allow us to study an interplanetary shock in considerable detail.

The shock front passed over OGO-5 between 1326:40 and 1326:50 UT and in the spacecraft frame the electric field turbulence had high frequency spectral peaks. This can be seen in Figure 3 where the nearly vertical lines in the $f(t)$ diagram have little amplitude below about 1.5 to 2.5 kHz. Very high resolution spectrograms with sweep repetition every 50 millisecond have recently been presented for this event (see Figure 3 of [4], and it has been shown that the $E$-field spectrum actually changed

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Fig. 3. Pioneer 8 and OGO-5 measurements of the April 5, 1968 storm. The Pioneer broadband channels give a qualitative measure of the noise intensity for $f \geq 100$ Hz. The relative amplitudes in bandpass channels are shown for the OGO-5 electric field noise bursts and the $f$-$t$ diagram gives the dynamic spectrum.
rapidly over these fine time-scales. This suggests that very short wavelength ($\lambda \approx 2$–3 Debye lengths) oscillations with $\omega/k \ll 400$ km/sec have been detected, and that Doppler effects provide significant frequency shifts. At this time the upstream solar wind plasma density was about 20 cm$^{-3}$ (M. Neugebauer, private communication), so that $f_p^+$ was nearly 1 kHz; reasonable Doppler shifts could then easily give an apparent frequency of (2–5) kHz, and we conclude that the April 5 observations are compatible with the interpretation that intense electrostatic ion sound waves develop in the shock region. Furthermore, the Pioneer 8 data show that more moderate enhanced noise levels do persist in the solar wind for many hours after the front has passed.

4. Whistler Mode Shocks

Figure 4 shows some Pioneer 8 and OGO-5 data taken during another sequence of solar disturbances early in rotation 1842. On March 14 a number of sudden commencements and sudden impulses were detected on the ground, and during this period the Pioneer 8 electric field experiment measured significantly enhanced VLF potentials. OGO-5 found that the magnetopause and shock were encountered at abnormally small radial distances, and the shock crossings were marked by an unusual and distinctive structure. The upper box in Figure 4 shows a magnetic field profile that

![Graph of magnetic field and electric field data]

Fig. 4. Data similar to Figure 3 for the disturbed March 14, 1968 bow shock crossing. The only strong low frequency ($f < 22$ kHz) electric fields detected here were the electric components of whistler mode bursts. Special purpose telemetry is not available to us on OGO-5 for $f > 22$ kHz, and we cannot display the dynamic spectrum for these 30 kHz signals.
bears a superficial resemblance to the one contained in Figure 1. However, there are two significant differences: (a) the field magnitude is approximately 2 to 2.5 times greater on March 14 than on March 12, and; (b) the frequency content of the magnetic compressions is much higher on March 14 (note that Figure 1 displays 30 sec worth of data while Figure 4 shows only 7 sec worth).

The central box in Figure 4 illustrates that moderate amplitude \( E \lesssim 1 \text{ mV/M} \) high frequency waves were generated in the shock region. These may represent electrostatic electron plasma oscillations (for \( N \approx 16/cm^3 \) (M. Neugebauer, private communication), \( \omega_{pe}/2\pi \approx 36 \text{ kHz} \)) and it can be seen that many of the impulses are found in the steep \( B \)-field minima. Although these high frequency waves are generally found near the bow shock, the March 14 event (and a few other crossings) are marked by an unusual absence of strong low frequency electrostatic noise related to ion sound waves. The only significant low frequency \( E \)-field waves detected here were the electric components of whistler mode waves with \( f \ll 560 \text{ Hz} \).

We do not yet understand what conditions determine when the bow shock microstructure is to be governed by electrostatic or electromagnetic wave excitation. However, the measurements displayed in Figure 4 show that at least on some crossings, whistler mode growth predominates.

5. Null Regions

On the downstream side of the April 5 shock (Figure 3) a very complex magnetic field profile is seen to be associated with intense VLF electric field noise. Figure 5 contains

![Figure 5](image_url)

**Fig. 5.** Enlarged view of a section of magnetosheath data for April 5, 1968. The field 'nulls' are found when the field rotates. The large amplitude electrostatic noise bursts are again detected where the steepest magnetic gradients are found.
an expanded plot of these data, and here the $E$-field calibrations are specifically inserted. The digital data rate for Figure 5 is 8 kilobits/sec, the $E$, $B$ samples are obtained every 144 millisecond, and it is clear that the full structure could not have been determined with a significantly lower sampling rate.

The vector magnetometer data on OGO-5 show that these configurations where $|B|$ dips nearly to zero are commonly detected in the outer regions of the magnetosheath. We call these field ‘nulls’ (a sharp increase in $|B|$, such as that observed at 1325:15 UT, is found very rarely), and we observe that the nulls always separate regions where $B$ has different orientations. This is illustrated in Figure 5 by the lowest box. It can be seen that rotations in $B$ do not always yield nulls, but that null regions require the rotations. Thus, it appears that these magnetosheath features are X-type nulls, as first proposed by Sonett [8]. (It is rather remarkable that in 1963 Sonett was already able to decide on the presence of X-type nulls in the magnetosheath using data from Pioneer 1. This probe made a single traversal of the sheath, and a spinning search coil was used so that $|B|$ was not known. However, the Pioneer 1 experiment had a high effective data rate and an extremely comprehensive analysis was performed.)

During the Pioneer 9 outbound pass of November 8, 1968, similar magnetic features were observed and superthermal protons were detected in the low field region [9]. One might try to interpret such an event as a simple diamagnetic null, however the $|B|$-field profiles generally argue against this evaluation. Increased field magnitudes are rarely found along the outer slopes, but for diamagnetic repulsion the ‘frozen-out field’ would have to appear on the shoulders.

The $E$-field amplitude distributions of Figure 5 indicate that very intense electrostatic noise develops on the flanks where the $B$-field compression produces a steep gradient. The top box shows that the $E$-field bursts have relatively high frequencies and they appear to exhibit little dispersion on this time-scale. (The horizontal line labeled ‘interference’ is the 2461 Hz OGO converter frequency. Note that the $f'(t)$ diagram of Figure 5 has not been precisely aligned with the digital data; however, the field nulls show up as dropouts in the nearly horizontal Rubidium magnetometer lines, and extremely precise correlation can be achieved by comparing the dropouts with the $|B|$ plot.)

We interpret the intense electrostatic noise as ion acoustic waves or related Buneman modes produced by current-driven two-stream instabilities, as discussed previously.

It is reasonable to suggest that the data shown in Figure 5 can illustrate the phenomenon of magnetic field annihilation or reconnection. When one component of the $B$ field reverses across a skewed current pinch of thickness $l$, field lines diffuse through the pinch to merge in time $t$, given by

$$t \sim \sigma l^2. \quad (1)$$

Here $\sigma$ is presumably the anomalous conductivity associated with the drift instability and with scattering of particles from the electrostatic waves. Some summary discussions of general reconnection phenomena are given by Axford, Dungey and Petschek in *The Solar Wind* [10], and it now seems likely that ion acoustic waves provide a major dissipation mechanism that allows the reconnection to proceed.
6. Wave-Wave Interactions

The idea that large amplitude oblique (compressional) whistler mode waves or solitary magnetic pulses with appropriate phase speeds can produce a standing bow shock was advanced in Section 2. If proposals of this type have any validity, then we should expect to detect occasional moving shock-like structures associated with whistlers, or solutions having 'wrong' phase speeds. Large amplitude magnetic gradients could still trigger two-stream electrostatic instabilities, but these events would lead to propagating disturbances, rather than the standing bow shock.

It now seems that such interactions are indeed present in the upstream solar wind. Long period oscillations \((T \simeq 20-60 \text{ sec in the spacecraft frame})\) with \(|A|/|B| \geq 0.5\) have been detected on Explorers 33–35, Vela 3, and finally on OGO-5. The high data rate capability of OGO-5 also allows detection of high frequency \((T \simeq 1-2 \text{ sec})\) damped electromagnetic tones that appear in the midst of the long period waves. The study of these bursts is far from complete at present, but it does appear that the magnetosonic waves in the upstream region can have field gradients steep enough to trigger electrostatic turbulence. An example of this upstream wave-wave interaction is given in Figure 2 of [7]. In that case (0925 on March 10, 1968), the OGO-5 LEPEDEA of Dr. L. A. Frank showed that significant fluxes of 4–7 keV protons were also present in the wind. Investigations of these wave-particle interactions are being pursued intensively at this time and no definitive conclusions are presently available. However, the results do suggest that the extremely low fluxes of energetic protons detectable with a LEPEDEA can have a profound effect on the upstream or interplanetary environment.

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