

Analysis and Interpretation of the Shocklike Electrostatic Noise Observed During the AMPTE Solar Wind Lithium Releases

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During the Active Magnetospheric Particle Tracer Explorers (AMPTE) solar wind lithium release on September 11, 1984, and again on September 20, 1984, an intense burst of electrostatic noise was observed near the upstream edge of the ion cloud. Comparisons with measurements by the IMP 6 and ISEE 1 spacecraft show that the spectrum and overall features of this noise are very similar to electrostatic noise observed at the earth's bow shock. A stability analysis using realistic parameters shows that the electrostatic noise can be accounted for by an ion beam-plasma instability caused by the solar wind proton beam streaming through the nearly stationary lithium cloud. The growth rate of this instability is largest when the ion density and solar wind proton density are similar, which explains why the noise only occurs near the outer edge of the ion cloud. The similarity to the noise in the earth's bow shock suggests that a shock may exist in the solar wind plasma flow upstream of the ion cloud. If the noise is associated with a shock, then it must be an electrostatic shock, since the ion cyclotron radii are too small for the existence of a MHD shock. Since the electrostatic instability occurs at phase velocities near the lithium thermal velocity, the electrostatic turbulence may play a role in heating the lithium ions and transferring momentum from the solar wind to the ion cloud. The noise may also play a role in the pitch angle scattering and diffusion of energetic electrons observed in the vicinity of the ion cloud. Because of the similarity to the solar wind interaction with the gaseous envelope of a comet, it is expected that similar types of wave-particle effects may occur upstream of comets.

1. INTRODUCTION

On September 11, 1984, and again on September 20, 1984, a cloud of lithium gas was released in the solar wind upstream of the earth's bow shock as part of the Active Magnetospheric Particle Tracer Explorers (AMPTE) program. Numerous effects were observed in the immediate vicinity of the releases, including (1) the creation of a dense, rapidly expanding cloud of ionized lithium, (2) the formation of a diamagnetic cavity, and (3) the occurrence of an intense shocklike burst of electrostatic noise in the region upstream of the cavity. The purpose of this paper is to present a detailed analysis of the shocklike electrostatic noise and to investigate the origin of this noise. Comparisons are also made with a similar type of noise observed in the earth's bow shock.

The primary objective of the AMPTE program is to use artificially injected barium and lithium ions as tracers to study the transport and energization of charged particles in the earth's magnetosphere, and a secondary objective is to study the physics of the injection process [Krimigis *et al.*, 1982]. Three spacecraft are involved in the project: the Ion Release Module (IRM), which carries the barium and lithium canisters; the United Kingdom Subsatellite (UKS), which orbits near the IRM to study the expansion and evolution of the ion cloud; and the Charge Composition Explorer (CCE), which searches for the tracer ions in the inner regions of the magnetosphere.

The data presented in this paper are from the plasma wave experiment on the IRM. The IRM is in a low-inclination,

highly eccentric orbit with an apogee geocentric radial distance of 19.0 R_E . During the September 1984 releases, the apogee was on the dayside of the earth near local noon. The ion cloud is produced by releasing two canisters containing lithium or barium in diametrically opposite directions from the IRM. Ten minutes after the release, the two canisters are exploded simultaneously at a distance of about 1 km from the spacecraft. The atoms vaporized by the explosion then form an expanding cloud of neutral gas, which sweeps over the spacecraft a few seconds after the explosion. Ultraviolet radiation from the sun subsequently ionizes the neutral gas, thereby producing a cloud of ionized gas. For a discussion of the physics of the ion cloud formation and expansion, see Haerendel [1983].

A variety of particle and field instruments on the IRM are used to analyze the plasma effects associated with the ionized gas cloud. For a list of these instruments and their characteristics, see Krimigis *et al.* [1982]. The measurements of particular interest for this paper are from the plasma wave instrument. The plasma wave instrument uses a 47-m tip-to-tip electric dipole antenna for electric field measurements and two search coil antennas for magnetic field measurements. The signals from the electric and magnetic antennas are processed by a variety of receivers and spectrum analyzers provided by three groups: from the University of Iowa, the Max-Planck-Institut, and The Aerospace Corporation. For a complete description of this instrumentation, see Häusler *et al.* [1985].

2. CHARACTERISTICS OF THE INTENSE ELECTROSTATIC NOISE

The overall features of the plasma wave observations are very similar for both the September 11 and September 20 lithium releases. Since a survey of the plasma wave observations is given by Häusler *et al.* [this issue], we will not repeat the detailed description of both events. For purposes of analyzing the origin of the intense electrostatic noise, it is sufficient to use the September 20 event as a model. The plasma interactions during this event tend to be the least complicated and most readily amenable to a theoretical analysis.

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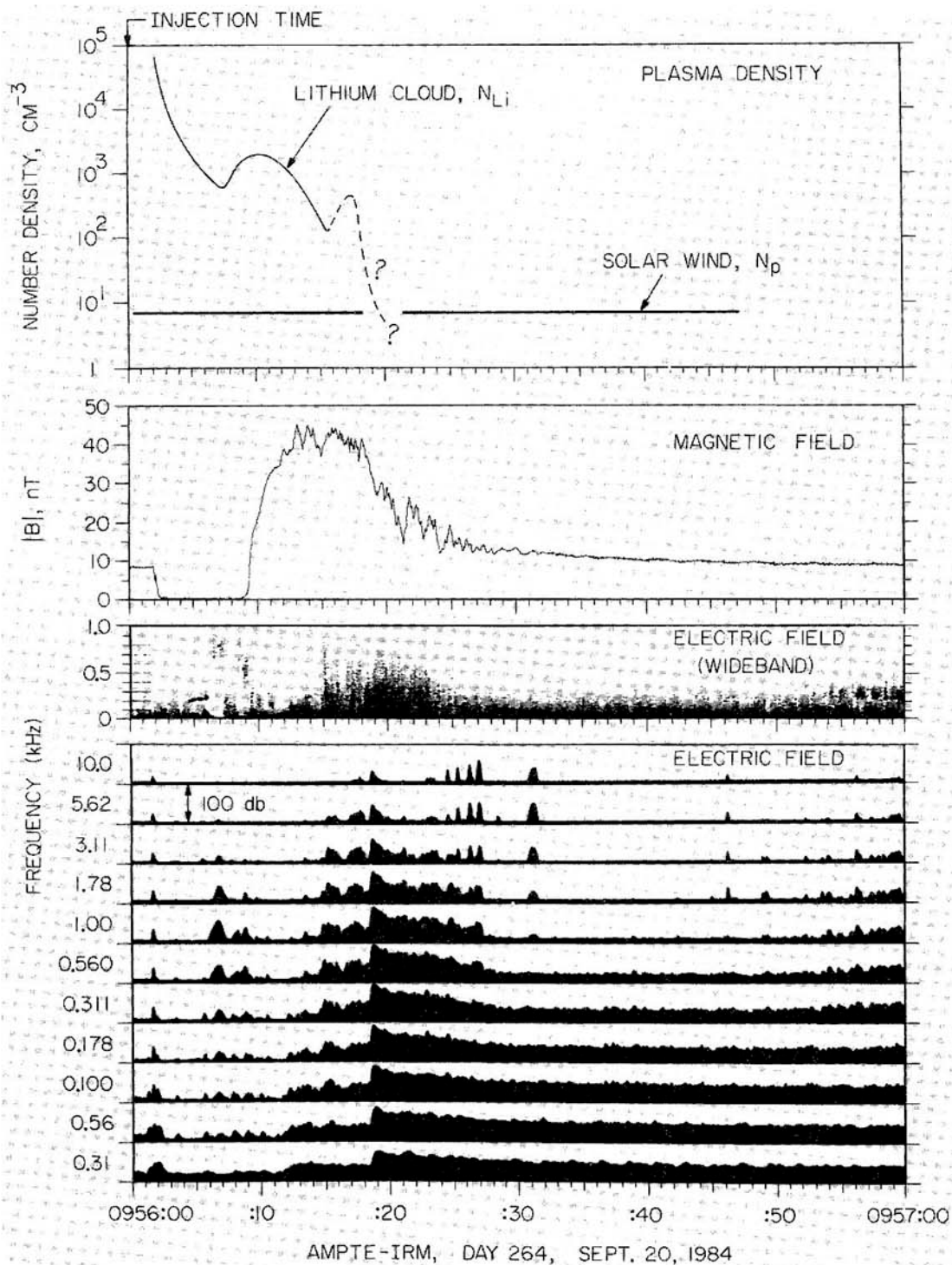


Fig. 1. A summary of the plasma density, magnetic field, and electric field observations for the September 20, 1984, solar wind lithium release. Note the intense burst of electrostatic noise from about 19 to 28 s after the injection, as the magnetic field returns to the upstream value. A somewhat similar burst of noise was observed following the September 11, 1984, lithium release.

A summary of the plasma density, magnetic field, and plasma wave electric field data obtained during the September 20 event is shown in Figure 1. The top panel shows the plasma density obtained from an analysis of electron plasma oscillations observed by the plasma wave instrument (R. R. Anderson et al., unpublished manuscript, 1985), the second panel shows the magnetic field from the magnetometer [Lühr et al., this issue], the third panel shows the electric field spectrum from the wideband receiver, and the bottom panel shows the

electric field intensities from the 16-channel plasma wave spectrum analyzer. The canisters of lithium were exploded at 0956:02 UT, near the left edge of the plot. About 0.2 s after the injection the plasma density jumps up to about 10^5 cm^{-3} , the magnetic field drops to near zero, and an impulsive disturbance occurs in the low-frequency electric field channels. These effects mark the arrival of the lithium ion cloud. The depressed magnetic field indicates that the spacecraft is in the diamagnetic cavity formed by the dense ion cloud. The geome-

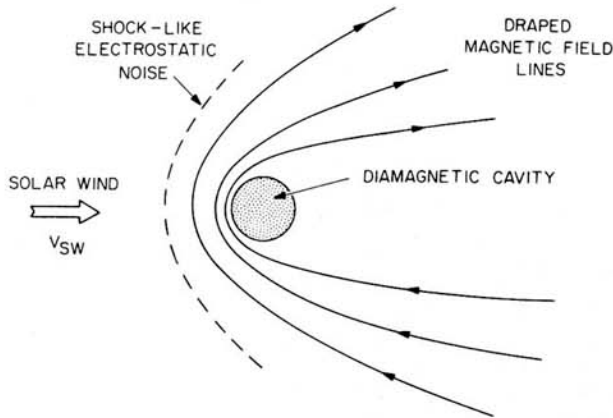


Fig. 2. A schematic illustration showing the inferred plasma and magnetic field configuration associated with the September solar wind ion releases. The intense burst of electrostatic noise is observed on the upstream edge of the region of draped magnetic field lines.

try of this cavity is illustrated in Figure 2. As the lithium ion cloud expands, the plasma density decreases. The cloud also starts to move downstream, away from the sun, because of stresses imposed by the solar wind. About 7 s after the explosion the magnetic field begins to increase. At this time the cloud has moved downstream to the point where the spacecraft is passing through the sunward boundary of the diamagnetic cavity. The spacecraft then enters a region of enhanced plasma density and strong magnetic field. The peak strength of the magnetic field is about 6 times stronger than the ambient solar wind magnetic field. This region of compressed plasma and strong magnetic field is caused by the "pileup" of plasma around the nose of the cloud due to the interaction

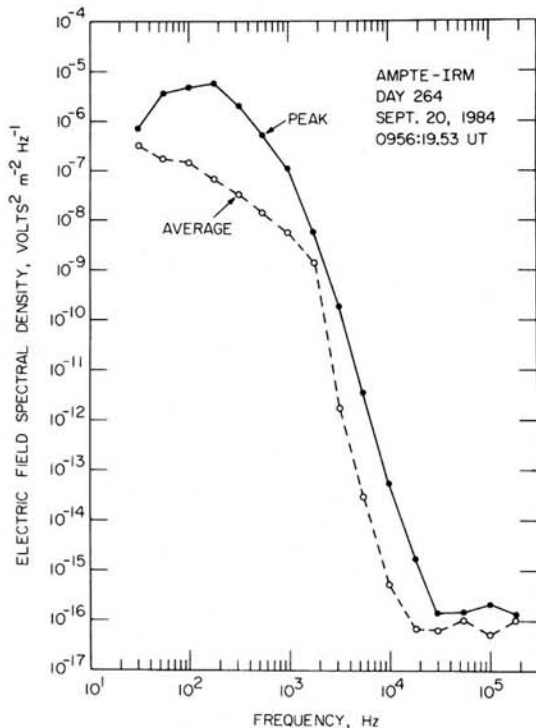


Fig. 3. The peak and average electric field spectrums for the September 20 event. The peak spectrum shows that the maximum electric field intensities occurred in the frequency range around a few hundred hertz. The intensities decrease rapidly at frequencies above a few kilohertz.

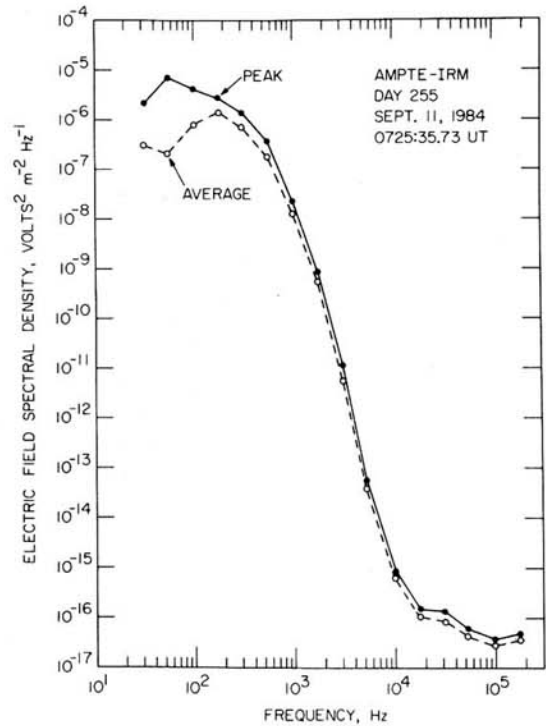


Fig. 4. The peak and average electric field spectrums for the September 11 event. Again, the peak electric field intensities are in the region around 100 Hz, with significant noise intensities extending up to a few kilohertz.

with the solar wind. The magnetic field is believed to be draped around the diamagnetic cavity as shown in Figure 2.

As the ion cloud moves farther downstream, a region of very intense electric field noise is encountered about 17 s after the injection. This region of intense electric field noise is located on the sunward side of the compression region, in a region where the magnetic field is returning to the preevent value. The region of intense electric field noise also appears to coincide with a brief increase in the plasma density. Because considerable uncertainty exists about the precise shape of the plasma density profile in this region (R. R. Anderson et al., unpublished manuscript, 1985), this portion of the plasma density profile is shown by dashed lines in Figure 2. The intense electric field noise continues for about 10 s, slowly decreasing in intensity as the magnetic field returns to the upstream value.

At no time during the event was any noise comparable to that shown in Figure 1 detected with the search coil magnetometers. The absence of a comparable magnetic component indicates that the noise is electrostatic, which is not surprising since no electromagnetic mode exists in the frequency range where the noise is observed (between the electron cyclotron frequency and the electron plasma frequency). The spectrum of the electrostatic noise is shown in Figure 3. Two types of spectrums are shown, labeled peak and average. The peak is the maximum electric field spectral density observed over a 1.0-s interval, and the average is the electric field spectral density averaged over a 50-ms interval. The time for the spectrums shown in Figure 3 is 0956:19.53 UT, which is near the point of maximum intensity. The peak and average broadband field strengths, integrated from 31 Hz to 178 kHz, are 40.4 and 6.6 mV m^{-1} , respectively. These intensities are among the most intense ever recorded by a space plasma wave experiment.

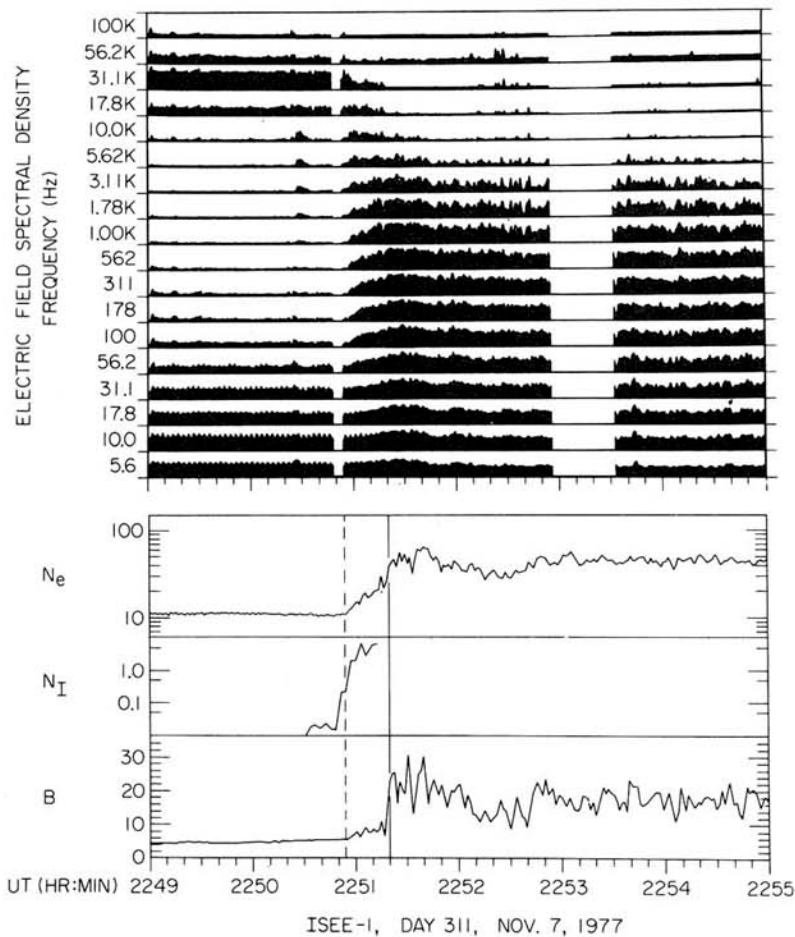


Fig. 5. The plasma density, magnetic field, and electric field measurements for a crossing of the earth's bow shock by the ISEE 1 spacecraft on November 7, 1977. The electrostatic noise observed on this and other shock crossings is very similar to the noise observed upstream of the AMPTE artificial ion clouds.

The noise in Figure 3 is characterized by a very broad peak that extends from a few tens of hertz up to a few hundred kilohertz. Above a few kilohertz the intensity drops very rapidly, to near the instrument noise level at frequencies above about 10 kHz. The peak spectrum shows a broad maximum at a frequency of about 178 Hz, and the average spectrum shows a discontinuity in the slope at about 1.78 kHz. These detailed features are probably not significant, since they vary somewhat from event to event. For example, the corresponding average spectrum for the September 11 event, shown in Figure 4, does not show a discontinuity in the slope. Also, the average spectrum for the September 11 event shows a peak at about 178 Hz, whereas the average spectrum for the September 20 event decreases monotonically over the entire frequency range measured.

High-resolution wideband spectrums, such as those shown in the third panel of Figure 1, show that the noise tends to be somewhat impulsive, consisting of many short bursts lasting only a fraction of a second. This impulsive character accounts for the large difference between the peak and average spectrums in Figure 3. The impulsive character of the noise also varies somewhat from event to event. The September 11 event in Figure 4 has a smaller difference between the peak and average intensities, which shows that the noise was less impulsive during this event. No evidence for spin modulation is evident in the electric field intensities, which indicates that the electric field, and hence wave vector direction, tends to be distributed over a broad range of angles.

3. IS THE ELECTROSTATIC NOISE ASSOCIATED WITH A SHOCK?

The location of the intense electrostatic noise upstream of the ion cloud raises the question of whether or not this noise is associated with a shock. For many years it has been known that an intense burst of electrostatic noise is present in the earth's bow shock [Fredricks *et al.*, 1968, 1970a, b; Rodriguez and Gurnett, 1975]. It is now widely believed that in a collisionless plasma this noise causes heating and dissipation very similar to those of collisions in an ordinary gasdynamic shock. The close similarity of the electrostatic noise to the noise in the earth's bow shock is illustrated in Figure 5, which shows a crossing of the earth's bow shock by the ISEE 1 spacecraft on November 7, 1977. The top panel of Figure 5 shows the electric field intensities, and the bottom three panels, from Paschmann *et al.* [1982], show the electron density N_e , the reflected ion density N_I , and the magnetic field strength B . The shock can be identified by the abrupt increase in the electron density and magnetic field strength from about 2250:55 to 2251:20 UT. This region of rapidly increasing plasma density and magnetic field strength is called the transition region. The top panel of Figure 5 shows that an intense burst of electric field noise is present in the transition region.

The similarities between the electric field noise upstream of the artificial ion cloud and the noise in the earth's bow shock are quite striking. In both cases the noise is almost completely electrostatic and extends over a broad range of frequencies,

from a few hertz to several kilohertz. An electric field spectrum of the noise observed in the earth's bow shock is shown in Figure 6. This spectrum is from the time of maximum intensity at 0251:20 UT. The similarity of this spectrum to the spectrums in Figures 3 and 4 is clearly evident. In both cases the noise extends with relatively high intensities from a few hertz to a few kilohertz and then decreases rapidly with increasing frequency. As in the case of the noise upstream of the artificial ion cloud, the detailed shape of the spectrum in the bow shock varies somewhat from event to event. In some cases the spectrum has a peak at a frequency of a few hundred hertz, similar to the example in Figure 4, whereas in other cases it is nearly flat, as in Figure 6. Wideband spectrums show that the noise in the bow shock is very impulsive and usually does not have a detectable spin modulation, so that it is very similar to the noise observed upstream of the artificial ion cloud. For a survey of representative spectrums of the electric field noise in the earth's bow shock, see *Rodriguez and Gurnett* [1975]. Although the overall features are similar, the noise associated with the artificial ion cloud is more intense than the noise in the bow shock, typically by a factor of 10 to 100.

To interpret the effects upstream of the ion cloud as a shock, certain basic conditions must be satisfied. First, the plasma must have a component of flow normal to the surface of the discontinuity. This condition is known to be satisfied, since the plasma instrument shows that the solar wind protons stream through the ion cloud. Second, the solar wind velocity must decrease as the plasma flows across the discontinuity. This condition also appears to be satisfied. For the September 20 event the UKS plasma instrument shows that the solar wind velocity decreases by about 50 km/s near the upstream edge of the cloud [Coates *et al.*, this issue]. The September 11

event shows a similar decrease in the solar wind velocity. Third, to qualify as a shock, the entropy must increase as the plasma flows across the discontinuity. Wave-particle interactions caused by the intense electric field noise upstream of the ion cloud certainly could cause an increase in entropy. However, the entropy production cannot be verified directly because the plasma instrument does not have sufficient space and time resolution to accurately determine the temperature and density variations in the region where the noise is observed.

The above considerations support the view that the noise upstream of the ion cloud could be associated with a shock, but they do not prove that it is a shock. If it is a shock, then it cannot be a conventional magnetohydrodynamic (MHD) shock. For a MHD shock the ion cyclotron radii must be small in comparison with the radius of curvature of the discontinuity; otherwise, magnetohydrodynamics would not apply. From relatively simple pressure balance considerations, we estimate that the radius of the diamagnetic cavity is about 30 km. For a representative solar wind ion temperature of 10^5 °K and a magnetic field strength of 8 nT it can be shown that the cyclotron radius of a solar wind proton is 56 km. Lithium ions injected into the solar wind at a relative velocity of 400 km/s have an even larger cyclotron radius, up to 2500 km. Since these ion cyclotron radii are larger than the scale size of the ion cloud, the upstream disturbance cannot be a MHD shock.

If the disturbance is not a MHD shock, then the only remaining possibility is that it is an electrostatic shock. Electrostatic shocks are characterized by a jump in the electrostatic potential on a spatial scale that is small in comparison with the ion cyclotron radii. Because the characteristic thickness of an electrostatic shock can be as small as a few Debye lengths, which is only about 100 m in the solar wind, an electrostatic shock could in principle occur upstream of the artificial ion cloud. Electrostatic shocks have received extensive theoretical study [Montgomery and Joyce, 1969; Forslund and Shonk, 1970; Tidman and Krall, 1971] and have been produced in laboratory plasmas [Ikezi *et al.*, 1973; Means *et al.*, 1973]. Both laminar and turbulent electrostatic shocks have been observed. Turbulent shocks are mainly associated with high Mach numbers, in which case the turbulence is produced by ions reflected from the electrostatic potential barrier at the shock. If the electrostatic noise observed upstream of the artificial ion cloud is caused by an electrostatic shock, it is almost certainly a turbulent shock, since the Mach number of the solar wind flow (8 to 10) is quite high.

4. ORIGIN OF THE ELECTROSTATIC NOISE

Since the solar wind protons stream almost uninhibitedly through the ion cloud, it is evident that an ion beam-plasma instability may be a good candidate for producing the electrostatic noise. This instability would then be similar to the mechanism responsible for the electrostatic noise in the earth's bow shock. For supercritical shocks, such as those shown in Figure 5, the electrostatic noise is closely correlated with the onset of ions (N_i) reflected from the bow shock [Gurnett, 1985]. These reflected ions produce an ion beam-plasma interaction that is very similar to the interaction that occurs as the solar wind protons stream through a stationary ion cloud.

Before we consider a quantitative analysis of the ion beam-plasma instability, it is useful to discuss the qualitative aspects of this instability. The ion distribution function in the vicinity of the ion cloud is illustrated schematically in Figure 7. The lithium ions have a drift velocity near zero, since they are born

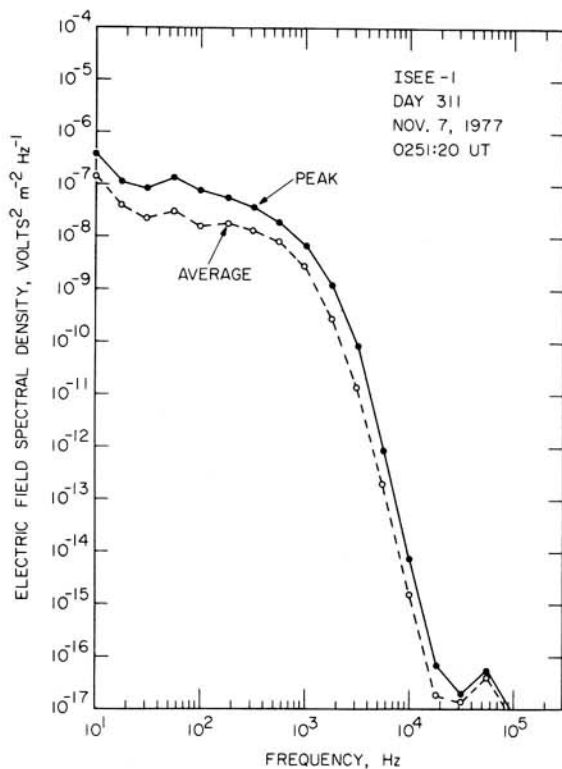


Fig. 6. The electric field spectrum at the time of maximum intensity for the shock crossing in Figure 5. Note the very close similarity to the artificial ion cloud spectrums in Figures 3 and 4.

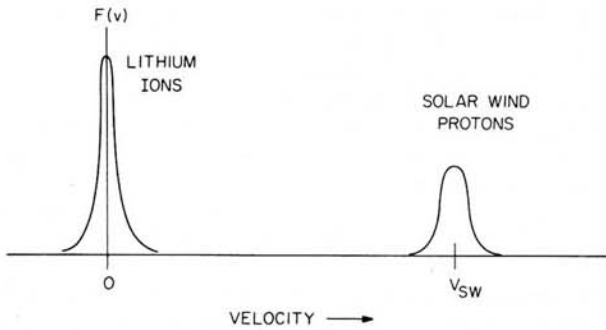


Fig. 7. A schematic representation of the ion distribution function in the vicinity of the artificial ion cloud. The lithium ions are born essentially at rest in the spacecraft frame of reference. The solar wind protons stream essentially uninhibitedly through the ion cloud with a velocity V_{sw} . This double-humped distribution is known to be highly unstable.

essentially at rest in the spacecraft frame of reference. The solar wind protons drift at a velocity corresponding to the upstream solar wind velocity, V_{sw} . The relative density of the lithium ions and solar wind protons varies with position in the ion cloud. Far upstream of the cloud the solar wind protons dominate, and in the dense central regions of the cloud the lithium ions dominate. The double ion distribution in Figure 7 corresponds to the classical ion beam-plasma interaction, first analyzed in detail by *Fried and Wong* [1966]. For a further discussion of the ion beam-plasma instability, see *Imre and Özizmir* [1974].

It can easily be shown that the growth rate of electrostatic instabilities in an unmagnetized plasma is determined by a reduced (one-dimensional) distribution function $F(v)$, which is the sum of the electron (e) and ion (i) distribution functions,

$$F(v) = F_e + \sum_i \frac{m_e}{m_i} F_i(v) \quad (1)$$

where the ion terms $F_i(v)$ have weighting factors given by the electron-to-ion mass ratio, m_e/m_i . The plasma is unstable when the reduced distribution function is sufficiently double humped to satisfy the Penrose criterion [*Krall and Trivelpiece*, 1973]. Because the electron-to-ion mass ratio is always very small, the ion terms must be sharply peaked and well separated for instability to occur. Because the thermal velocities of both the lithium ions and the solar wind protons are much smaller than the solar wind velocity, the distribution functions tend to satisfy this condition. However, it is also necessary to consider the role of the electrons. The electron distribution is expected to consist of two components: a "cold" component associated with the lithium photoionization, and a "hot" component associated with the solar wind electrons. Because the cyclotron radius of the electrons is small in comparison with the diameter of the cloud, both components are expected to drift at the $\mathbf{E} \times \mathbf{B}$ drift velocity, V_d . As long as the current is reasonably small, V_d is expected to lie between the drift velocities of the lithium ions and the solar wind protons, as illustrated in Figure 8. The reduced distribution function then has two double humps, one associated with the lithium ions and electrons, and the other associated with the electrons and solar wind protons. Two instabilities are then expected, one with phase velocities $0 < \omega/k < V_d$, and the other with phase velocities $V_d < \omega/k < V_{sw}$. These instabilities only occur if the lithium ion and solar wind proton densities are somewhat comparable. Otherwise, the double hump associated with the minority ion disappears, because the "beam" density is too low, and the double hump associated with the majority ion

disappears, because the electrons drift at essentially the same velocity as the majority ion. These basic facts provide a simple explanation for why the noise only occurs near the outer boundary of the ion cloud. It is only in this region that the lithium ion and solar wind proton densities are comparable (see Figure 1).

To perform a detailed stability analysis, we assume that the plasma distribution function consists of four Maxwellian components representing the lithium ions, the solar wind protons, the hot solar wind electrons, and the cold lithium photoelectrons. Each component is characterized by a density, a temperature, and a drift velocity. For the September 20 event the parameters that are reasonably well known are (1) the lithium drift velocity, which is essentially zero, (2) the solar wind velocity V_{sw} , which is about 460 km/s [*Paschmann et al.*, this issue], (3) the lithium and solar wind proton densities, N_{Li} and N_p , which are shown in Figure 1, (4) the solar wind proton temperature T_p , which is about 10^5 °K [*Coates et al.*, this issue], and (5) the hot electron temperature T_e^h , which at energies above about 50 eV is about 5×10^5 °K [*Paschmann et al.*, this issue]. Parameters that are unknown because they cannot be measured by the plasma instrument are (1) the lithium ion temperature T_{Li} , (2) the cold (photoelectron) temperature T_e^c and density N_e^c , and (3) the drift velocity of the electrons, V_d .

To proceed further, suitable choices must be made for the unknown parameters. It is believed that the chemical reaction responsible for vaporizing the lithium yields a temperature of about 2×10^3 °K (G. Haerendel, personal communication, 1985). Although the lithium ions could be colder owing to time-of-flight effects, we will adopt the value $T_{Li} = 2 \times 10^3$ °K for the lithium ion temperature. Since nothing is known about the photoelectrons associated with the lithium ionization, the best that can be done is to consider two extreme situations. During the early phase of the ion cloud expansion it is likely that the photoelectrons are bound to the ion cloud by the ambipolar electric field. In this case the cold electron density is equal to the lithium ion density, $N_e^c = N_{Li}$. Macroscopic charge neutrality then implies that $N_e^h = N_p$. Since the photoelectrons are ejected from the lithium ions with an energy distribution comparable to the characteristic energy of the solar ultraviolet spectrum (~ 1 eV), it is likely that the cold electron temperature is about 10^4 °K. We will adopt the value $T_e^c = 10^4$ °K. During the later phase of the ion cloud expansion the ambipolar electric field eventually disappears, and the photoelectrons escape. The photoelectron density is then zero, $N_e^c = 0$. Macroscopic charge neutrality then implies that $N_e^h = N_p + N_{Li}$. Finally, we must consider the electron drift velocity. As a first approximation the $\mathbf{E} \times \mathbf{B}$ drift velocity can

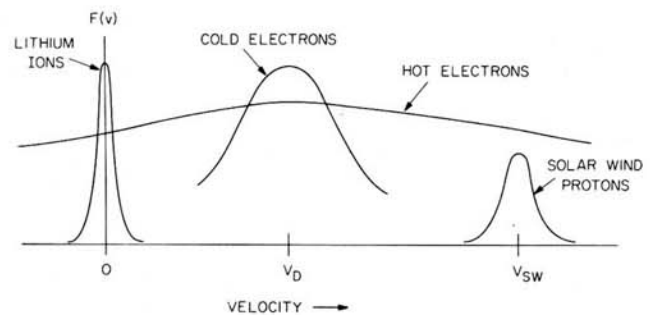


Fig. 8. A model for the cold electron distribution, in which the cold and hot electrons both drift at a velocity V_d that is determined by the $\mathbf{v} \times \mathbf{B}$ electric field. This model applies mainly to the motion perpendicular to the magnetic field.

be estimated by assuming that the net current in the plasma is zero. Later, we will consider the effect of a finite current. Using the condition for macroscopic charge neutrality, the zero current condition gives

$$V_d = \frac{N_p}{N_p + N_{Li}} V_{sw} \quad (2)$$

During the early dense phase of the ion cloud expansion, where $N_{Li} \gg N_p$, the electron drift velocity is near zero, and during the later tenuous phase, where $N_{Li} \ll N_p$, the electron drift velocity is near the solar wind velocity.

Using the above parameters, the frequency ω and growth rate γ of electrostatic waves can be calculated from the electrostatic dispersion relation, which for a Maxwellian distribution is

$$D(\omega, \gamma) = 1 + \sum_s \frac{1}{(k\lambda_{Ds})^2} [1 + z_s Z(z_s)] = 0 \quad (3)$$

where the summation is over all components (s), k is the wave number, λ_{Ds} is the Debye length of the s th component, and Z is the plasma dispersion function [Fried and Conte, 1961]. The parameter z_s is a dimensionless quantity given by

$$z_s = \left(\frac{m_s}{2\kappa T_s} \right)^{1/2} \left(\frac{\omega}{k} + i \frac{\gamma}{k} \right) \quad (4)$$

where m_s is the mass of the s th component and κ is Boltzmann's constant. The dispersion relation has been solved numerically for ω and γ using the Muller method [Muller, 1956]. Since it is not known whether a cold electron component is in fact present, the dispersion relation was analyzed for two extreme cases. First, it was assumed that $N_e^c = N_{Li}$. This case represents the situation where cold electrons associated with the lithium photoionization are still bound to the ion cloud.

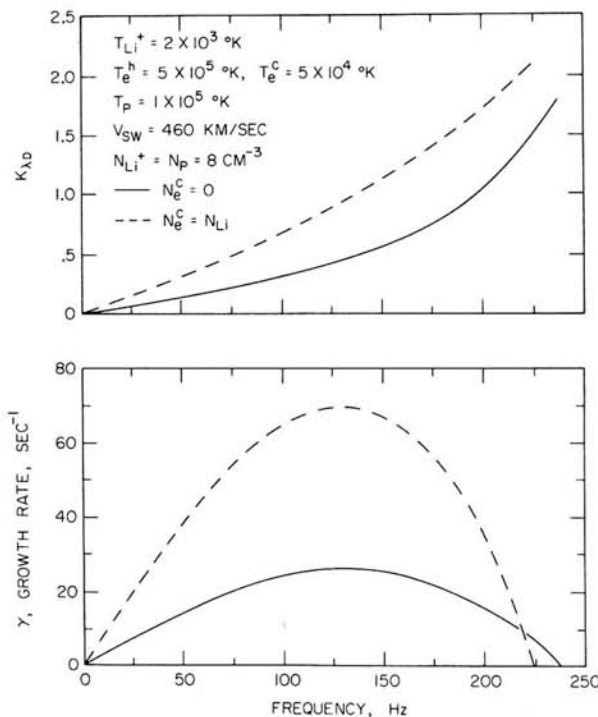


Fig. 9. Plots of the growth rate γ and normalized wave number $k\lambda_{D0}$, as a function of frequency for the instability associated with the minimum of $F(v)$ between 0 and V_D . The solid lines are for $N_e^c = 0$, and the dashed lines are for $N_e^c = N_{Li}$.

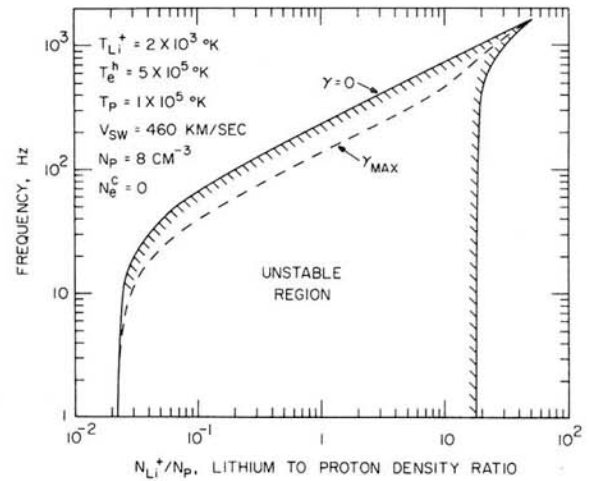


Fig. 10. The frequencies of marginal stability, $\gamma = 0$, and maximum growth rate, γ_{max} , as a function of the lithium-to-proton density ratio, N_{Li}/N_p . This case is for $N_e^c = 0$. Note the limited range of N_{Li}/N_p over which instability occurs. Also, note that the maximum frequency of the instability compares favorably with the observed frequency range of the noise in Figures 3 and 4.

Second, it was assumed that $N_e^c = 0$. This amounts to assuming that all of the photoelectrons have escaped from the cloud and that no cold electrons are present.

Of the two instabilities discussed earlier, the growth rate computations show that the instability with phase velocities between 0 and V_D is the most important. The reason is that the lithium ion temperature, $T_{Li} = 2 \times 10^3$ °K, is much lower than the proton temperature, $T_p = 1 \times 10^5$ °K, which makes the double hump associated with the lithium ions and electrons much more pronounced than the double hump associated with the electrons and protons. The instability with phase velocities between V_D and V_{sw} only occurs for proton temperatures less than about 3×10^4 °K. Since the measured proton temperature is 1×10^5 °K, this instability never occurs.

A representative growth rate computation for the instability between 0 and V_D is shown in Figure 9. The bottom panel shows the growth rate γ plotted as a function of frequency, and the top panel shows the wave number $k\lambda_{D0}$, normalized by the Debye length, plotted as a function of frequency. The lithium density and proton density are assumed to be equal, which represents the most unstable condition. The solid curve gives the case where $N_e^c = 0$, and the dashed curve gives the case where $N_e^c = N_{Li}$. Both cases give large growth rates, 25 s^{-1} and 72 s^{-1} , over a broad range of frequencies, up to about 250 Hz. This range of frequencies is in good agreement with the spectrums in Figures 3 and 4, which show that the most intense noise occurs at frequencies from a few tens of hertz up to a few hundred hertz.

Because the relative densities of the lithium ions and protons vary over a large range, it is useful to investigate the instability as a function of the lithium-to-proton density ratio N_{Li}/N_p . Figures 10 and 11 show the frequency of marginal stability ($\gamma = 0$) as a function of N_{Li}/N_p . The dashed line labeled γ_{max} gives the frequency of maximum growth rate. Figure 10 is for the case $N_e^c = 0$, and Figure 11 is for the case $N_e^c = N_{Li}$. In both cases the instability occurs over a broad region, which shows that the basic mechanism is relatively insensitive to the assumed parameters. Figures 10 and 11 also confirm the previously mentioned fact that the instability only occurs over a limited range of lithium-to-proton density ratios. If the lithium-to-proton density ratio is less than about

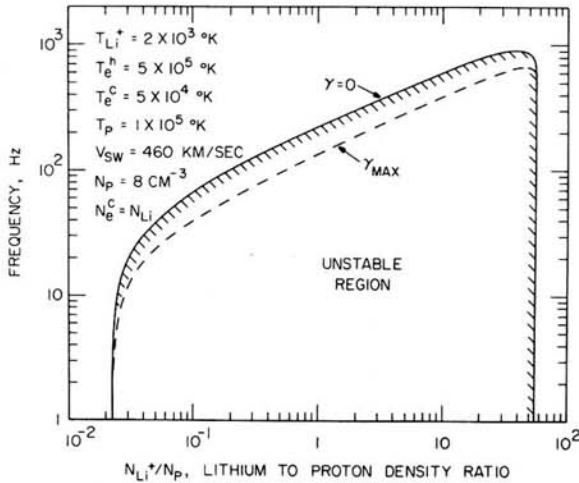


Fig. 11. The frequencies of marginal stability, $\gamma = 0$, and maximum growth rate, γ_{\max} , as a function of the lithium-to-proton density ratio, N_{Li^+}/N_p . This case is for $N_e^c = N_{\text{Li}}$.

2.5×10^{-2} , the instability ceases, and if the ratio is above about 50, the instability again ceases.

Although the cold electron temperature does not have a major effect on the instability boundaries, it does effect the growth rate somewhat. The maximum growth rate is shown in Figure 12 as a function of the density ratio N_{Li^+}/N_p . The solid line is for the case $N_e^c = 0$, and the dashed line is for the case $N_e^c = N_{\text{Li}}$. As can be seen, the growth rate increases when the cold electrons are present. This dependence apparently occurs because the Landau damping decreases as the electron temperature decreases, which causes higher growth rates.

It can easily be shown that the growth rates in Figure 12, typically $25\text{--}75 \text{ s}^{-1}$, are more than adequate to produce the observed intensities. From Figure 9 the group velocity $\partial\omega/\partial k$ is estimated to range from about 5.3 to 50 km/s. Taking a representative group velocity of 50 km/s and a path length of 30 km, a wave packet would propagate through the unstable region in 0.6 s. For a representative growth rate of 25 s^{-1} the wave amplitude would grow by a factor of e^{15} . Waves of lower group velocity grow to even larger amplitudes. These simple estimates show that in a very short time the waves should grow to very large amplitudes. Although the detailed shapes of the spectrums in Figure 3 and 4 are controlled by nonlinear effects, the basic frequency range where the noise occurs appears to be accounted for by this linear stability analysis.

We now return to the zero current assumption. It is evident from the magnetic field variations that finite currents exist in the region where the noise occurs. The main effect of a current is to shift the electron drift velocity in relation to that given by (2), which assumes zero current. Using representative values for the magnetic field variation, $\Delta B \approx 35 \text{ nT}$, and scale size, $\Delta L \approx 200 \text{ km}$, of the magnetic field structure, the current density is estimated to be $0.14 \mu\text{A m}^{-2}$. For an electron density of 8 cm^{-3} this current produces a shift in the electron drift velocity of about 25%. This shift is an upper limit, since in the denser region of the cloud the shift required to produce the required current is smaller. Figure 13 shows the effect of a $\pm 25\%$ shift in the electron drift velocity for the case $N_e^c = N_{\text{Li}}$. Somewhat similar results are obtained for the case $N_e^c = 0$. As can be seen, a positive shift in the drift velocity (toward V_{sw}) increases the size of the unstable region, and a negative shift decreases the size of the unstable region. Generally, the effect of the current is quite small. Therefore the basic insta-

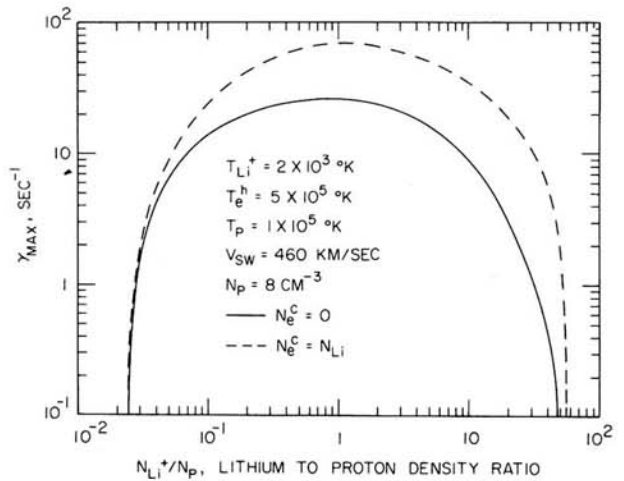


Fig. 12. The maximum growth rate of the ion beam-plasma instability as a function of the lithium-to-proton density ratio. Note that the highest growth rate occurs when $N_{\text{Li}} = N_p$. This result also agrees with the observations in Figure 1, which show that the most intense noise occurs at about the time that $N_{\text{Li}} \approx N_p$.

bility is an ion beam-driven instability and not a current-driven instability. The currents that exist in the upstream boundary region are simply too small to play a major role in the stability considerations.

5. CONCLUSION

We have presented a detailed analysis of the shocklike electrostatic noise observed upstream of the AMPTE artificial ion clouds and have described an ion beam-plasma instability that can account for the main features of this noise. Comparisons with other spacecraft measurements show that this noise is very similar to the electrostatic noise observed in the earth's bow shock. This similarity suggests that a shock may be present in the solar wind flow upstream of the ion cloud. The

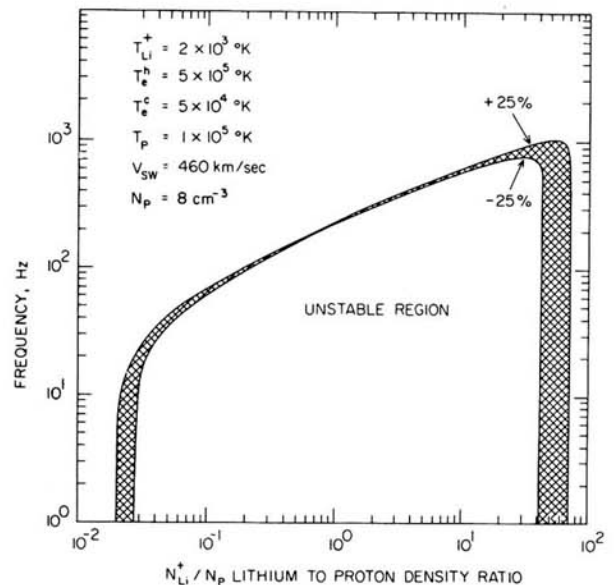


Fig. 13. Marginal instability boundaries, comparable to Figure 11, showing the effect of a current. The cross-hatched region shows the variation in the $\gamma = 0$ boundary for a $\pm 25\%$ variation in the electron drift velocity. These limits represent the maximum variations that could be produced by the currents in the upstream boundary region.

available data do not confirm the existence of a shock but also do not rule out the possibility. If the noise is associated with a shock, then the shock cannot be a MHD shock, since the ion cyclotron radii are large in comparison with the radius of curvature of the discontinuity. The most likely possibility is that the noise is associated with an electrostatic shock. This possibility is supported by the fact that laboratory experiments [Ikezi *et al.*, 1973] demonstrate that turbulent electrostatic shocks can be produced by injecting an ion beam into a plasma at rest, a physical situation qualitatively similar to injecting an ion cloud into the supersonically flowing solar wind.

An investigation of the instabilities caused by a solar wind proton beam streaming through a nearly stationary lithium ion cloud shows that the basic features of the electrostatic noise can be accounted for by an electrostatic ion beam-plasma instability. Using realistic parameters, it is found that the ion beam-plasma instability occurs for a range of lithium-to-proton density ratios between about 2.5×10^{-2} and 50. These limits explain why the noise only occurs near the outer edge of the ion cloud, in the region where the lithium-to-proton density ratio is near unity. The maximum growth rates increase if cold electrons associated with the lithium photoionization are present in the plasma. Currents do not play an important role in generating the noise.

At present the importance of the electrostatic noise has not been established. The noise is very intense and occurs in a region of elevated electron temperatures. Although the main electron energization is thought to be caused by adiabatic acceleration in the magnetic field upstream of the cloud [Paschmann *et al.*, this issue], the noise may play a role in the pitch angle scattering and diffusion of these electrons. If the noise is associated with an electrostatic shock, then the turbulent electric fields probably play an important role in the ion heating and dissipation in the shock. Since the phase velocity of the unstable waves is near the lithium thermal velocity, the turbulence should be very effective at heating the lithium ions.

It is likely that the intense electrostatic noise observed during the AMPTE ion releases is closely related to a variety of other situations in which intense electric field noise is produced by a neutral gas interacting with a rapidly moving plasma. These situations include (1) intense electric field noise associated with cesium ion release in the earth's ionosphere [Kintner *et al.*, 1980], (2) intense electrostatic noise observed in the vicinity of the space shuttle [Shawhan and Murphy, 1984], apparently caused by an interaction of gases from the shuttle with the surrounding ionosphere, and (3) electric field noise observed by Voyager 1 in the vicinity of Titan [Gurnett *et al.*, 1981]. Because of the close similarity of the lithium releases to the gaseous envelope around a comet, it will be interesting to see if a comparable type of noise is observed during the forthcoming flybys of the comets Giacobini-Zinner and Halley.

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