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The Role of Plasma Wave Turbulence in the

Formation of Shock Waves in Collisionless Plasmas:

Final Report on

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ABSTRACT

This is a report on the status as of September 1987 of our study of the role of plasma wave turbulence in the terrestrial bow shock.

In pursuit of that study we have compiled a data set containing measurements from variety of instruments for approximately 100 shock crossings, and have plotted the plasma wave profiles of these shocks in conjunction with their magnetic field data. Analysis of these profiles has lead to a number of important new results, which include the following observations.

(1) Three shock-associated emissions are seen in the plasma wave data: upstream electron plasma oscillations; ion acoustic noise; and low frequency electromagnetic noise. Profiles of the ion acoustic and lower frequency noise are quite similar. Each generally exhibits two scale lengths: wave intensity begins gradually building up 10's of seconds upstream, increases abruptly at the forward edge of the ramp, peaks within the ramp, and then decays to a steady downstream value. Electron plasma oscillations die away as the shock is approached, disappearing within the foot of supercritical shocks, and lasting midway through the ramp of subcritical shocks.

(2) This data set has provided the first comprehensive set of measurements of shock-associated waves in the range of the lower hybrid frequency, and has demonstrated that the observed waves are consistent with generation by the kinetic cross field streaming instability.

(3) The observation that the foot-associated waves are present upstream of even nominally subcritical shocks implies that a definition of the subcritical-supercritical transition which invokes the presence or absence of reflected ions as a marker requires modification. Reanalysis of shock overshoots, which was provoked by the plasma wave observations, has in fact lead to the conclusion that no firm evidence exists for a sharp subcritical/supercritical transition.

(4) Wave measurements have been shown to be in quantitative agreement with theoretical analyses of resistive heating at subcritical shocks, and have supported the predicted predominance of lower-hybrid-like modes over ion acoustic noise in the production of actual plasma heating.

(5) Evidence for variable shock normal angles is seen upstream from nominally quasiparallel shocks.

(6) Study of our data set lead to the discovery of the first cases of very strong electron heating observed at the terrestrial bow shock.

INITIAL OBJECTIVE

We proposed to provide more detailed wave measurements, and then to subsequently use these measurements and plasma heating data in making quantitative tests of theory. The initial step in our study, the construction a series of maps of plasma wave intensities referenced to magnetic field structures, was completed within the first year and the quantitative analysis has proceeded in several directions since then.

Figure 1 presents an example of our dual profile maps, with characteristic plasma wave emissions referenced to the magnetic field profile. Channels representing electron plasma oscillations (31.1 kHz), ion acoustic noise (562 Hz) and containing the lower hybrid frequency (5.6 Hz) are shown. Work with similar profiles has produced a number of interesting observations, which are outlined in the following sections.

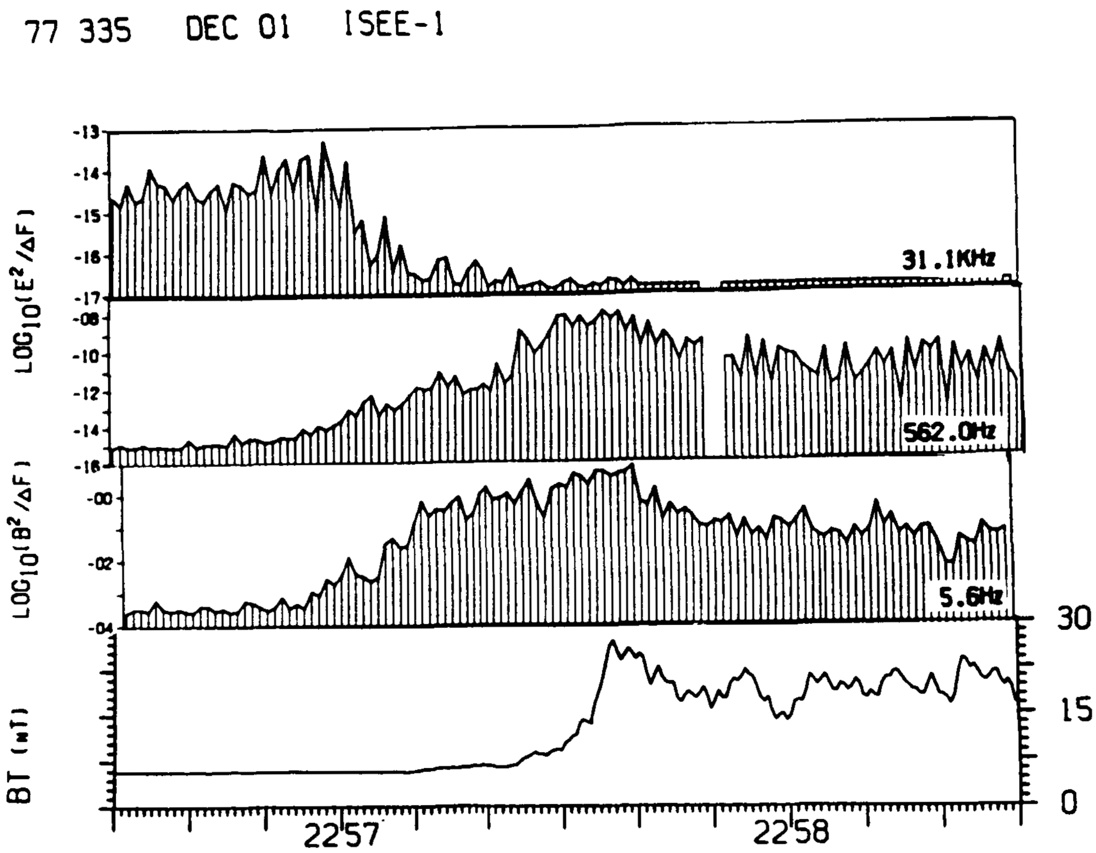

Figure 1. Plasma Wave and Magnetic Field Profiles.

PLASMA WAVE PROFILES

There are two general types of emissions which rise dramatically in intensity as the shock is approached. They are a mid-frequency (200–800 Hz) electrostatic "ion acoustic" emission and low frequency electromagnetic noise. The two emissions generally follow the same pattern with respect to shock structure. In both cases the noise growth has two scale lengths: wave intensity begins gradually building up 10's of seconds upstream, increases abruptly at the forward edge of the ramp, peaks within the ramp, remains steady for several seconds, and then decays within the overshoot to a steady downstream value. The upstream extent of the noise is correlated with the turnaround distance for specularly relfected ions. Similar patterns are seen in the cases of subcritical and supercritical shocks.

The narrow band high frequency electron plasma oscillations, on the other hand, die away as the shock is approached, disappearing within the foot of supercritical shocks, and persisting up until the ramp in subcritical cases. The plasma oscillations and foot ion acoustic noise are anticorrelated.

LOW FREQUENCY NOISE

A number of lower-hybrid-like instabilities have been suggested as sources of shock dissipation, but the lower hybrid frequency is generally approximately 10 Hz in the solar wind upstream of the earth, and observations in this frequency range have been scarce. The IMP plasma wave instruments did not cover this frequency range, and in the ISEE instruments, where the frequency range is sufficient, strong background often obscures the signals. We have managed to assemble a set of approximately 60 shocks however where clear shock-associated signals are seen in the lowest channels. Study of these shocks has enabled us to put together the first comprehensive description of lower-hybrid-like noise in a truly collisionless shock (Mellott and Greenstadt, unpublished manuscript). These data are generally consistent with the hypothesis that the kinetic cross field streaming instability is a major source of low frequency plasma wave noise at the earth's bow shock.

SUBCRITICAL/SUPERCRITICAL TRANSITION

We have argued (Greenstadt and Mellott, J. Geophys. Res., 92, 4730, 1987) that the upstream ion acoustic and lower hybrid noise are generated by ions reflected gyrating ions. In this case, the presence of an upstream foot in every one of the shocks in our data set has an important implication. It is evidence that there are always some reflected ions present, regardless of whether the magnetic field profile exhibits the supercritical foot and overshoot or not. It appears incorrect to define the subcritical/supercritical transition solely in terms of the presence or absence of reflected ions, a result which calls for a reconsideration of the significance of Edmiston and Kennel's (J. Plasma Phys., 32, 429-442, 1984) first critical Mach number.

The lack of a clear transition in the plasma wave data lead us to reconsider previous reports of a clear critical Mach number threshold for the appearence of overshoots in shock magnetic field profiles. In order to understand this apparent discrepancy we rechecked the overshoot results, and found that the earlier reported sharp threshold was an artifact resulting from the use of imprecise solar wind parameters. This analysis and its implications for the nature of very high and very low Mach number shocks are described in Mellott and Livesey (J. Geophys. Res., in press, 1987).

COMPARISONS WITH THEORY

One of our goals was to provide precise enough descriptions of the plasma wave emissions that quantitative comparisons with theory could be made. This required developing proper averaging techniques and collecting the appropriate solar wind data so that normalizations could be made.

One result of this development is that we have been able to compare measured wave intensities with those predicted in the comparison of the relative roles of ion acoustic and modified two stream instabilities in subcritical shocks carried out by Winske et al. (J. Geophys. Res., 92, 4411, 1987). This work showed that observed ion acoustic wave levels are far too low to account for the observed heating, while intensities at low frequencies are much closer to those required.

QUASIPARALLEL SHOCKS

This study has also produced interesting results in the regime of the quasiparallel shock. Shock crossings are difficult to pick out in the plasma wave data associated with these shocks because the region upstream from quasiparallel shocks is already filled with plasma wave noise. We have however found an interesting pattern in this upstream noise, which appears to reflect important shock processes. We observe, as can be seen in Figure 2, that the amplitudes of the upstream electron plasma oscillations (31.1 kHz) and ion acoustic noise (e.g., 3.11 kHz) vary (inversely) on the 30 second time scale.

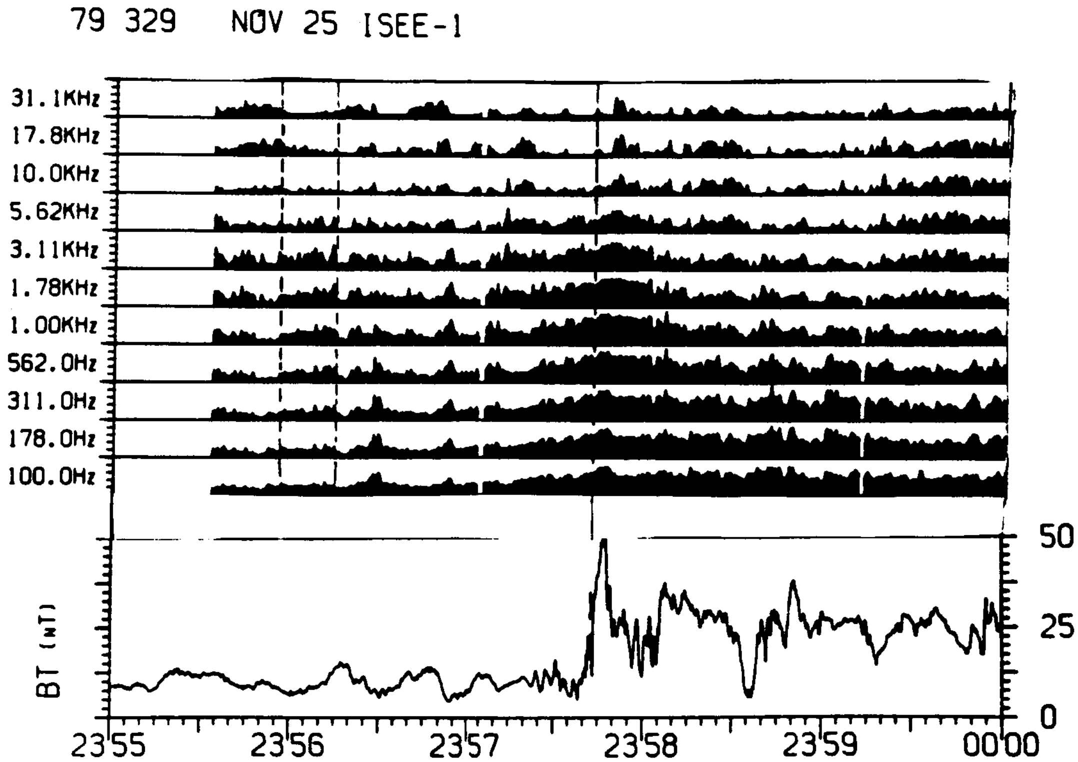

Figure 2. Quasiparallel Bow Shock: Plasma Wave Profile.

These observations are consistent with those of Greenstadt and Mellott, (Geophys. Res. Lett., 12, 129-132, 1985) who showed that the convection of large amplitude low frequency waves into a nominally quasiparallel shock results in local geometric conditions which vary from nearly parallel to nearly perpendicular. This variable shock normal angle is presumably being reflected in the periodic change of wave character.

ELECTRON HEATING

Previous reports generally supported the generalization that the earth's bow shock produces relatively little electron heating. Interest in anomalous electron heating revived recently however with the discovery of strong heating at the Jupiter shock. We picked out of our data set cases as similar as possible to those of Jupiter in order to see if similar effects might occur within the terrestrial data set. What we discovered in doing this was that in fact very strong electron heating can occur at the earth.

This is demonstrated in Figure 3, where the electron heating across the shocks in our data set is plotted as a function of shock strength as parameterized by the magnetic field ratio. There are clearly a number of shocks, clustered about the dashed line, where the heating is essentially adiabatic, but there are also a number of cases where the heating is very much stronger, in fact stronger than that observed at Jupiter. The existence of this strong heating, and its parametric dependences are discussed in a paper which we prepared in collaboration with Michelle Thomsen (Thomsen et al., J. Geophys. Res., in press, 1987).

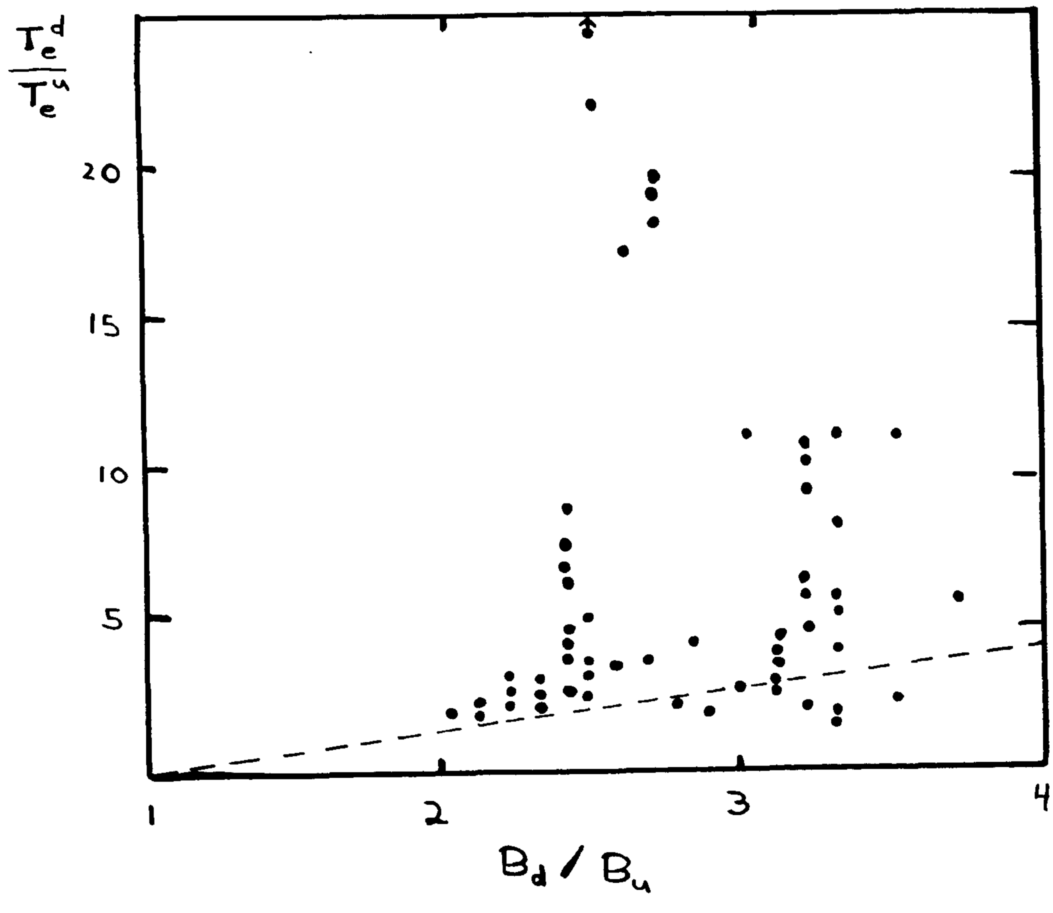

Figure 3. Electron Heating as a Function of Shock Strength. Ratio of Downstream to Upstream Electron Temperature is Plotted Versus Downstream to Upstream Magnetic Field Ratio.

SUMMARY

This study has produced a number of important results:

(1) There is strong electromagnetic turbulence in the range of the lower hybrid frequency associated with most shock crossings, and its characteristics are generally consistent with its generation via the kinetic cross field streaming instability.

(2) The maximum intensity in both ion acoustic and lower hybrid channels occurs within the shock ramp.

(3) Every shock in the data set has an upstream plasma wave foot, most likely driven by reflected gyrating ions. The presence of these feet upstream of nominally subcritical shocks indicates a need for more careful definition of the subcritical-supercritical transition.

(4) Electron plasma oscillations persist up to the ramps of subcritical shocks, and begin decaying at the front edge of the feet of supercritical shocks. Their intensity is anticorrelated with the amplitude of the foot ion acoustic noise.

(5) Wave measurements are in quantitative agreement with theoretical analyses of resistive heating in subcritical shocks.

(6) Evidence for variable shock normal angles is seen upstream from nominally quasiparallel shocks.

(7) Very strong electron heating is observed on occasion at the earth's bow shock.

POST SCRIPT

Establishment of this data set has aided significantly in increasing our understanding of the varieties and sources of plasma wave turbulence associated with the earth's bow shock. We have also, however, in the past two years come to a much better understanding of the role of these waves in shock dissipation. Unfortunately for those of us who are fond of wave particle interactions, it appears that in fact wave turbulence has relatively little to do with plasma heating at collisionless shocks (see discussion in Mellott, 1986). This was already clear in the case of ions when this study began: the major source of ion dissipation at most bow shocks is clearly the reflection process. It is also becoming clear that the major factor in electron heating is the interaction between the electron distribution and the shock potential, and that wave particle interactions play only a secondary role in shock physics. Important questions about the plasma physics associated with the generation and action of shock associated plasma waves remain however, to which further analysis of the data set produced in this study should provide important input.

TALKS and PUBLICATIONS

Publications regarding this work have included:

Greenstadt, E. W., and M. M. Mellott, Plasma wave evidence for reflected ions in front of subcritical shocks observed by ISEE 1 and 2, J. Geophys. Res., 92, 4730-4734, 1987.

Mellott, M. M., Plasma wave signatures of collisionless shocks, and the role of plasma wave turbulence in shock formation, Adv. Space Res., 6, 25-30, 1986.

Mellott, M. M., and E. W. Greenstadt, Plasma waves in the range of the lower hybrid frequency: ISEE 1 and 2 observations at the Earth's bow shock, to be submitted to J. Geophys. Res., 1987.

Mellott, M. M. and W. A. Livesey, Shock overshoots revisted, J. Geophys. Res., in press, 1987.

Thomsen, M. F., M. M. Mellott, J. A. Stansberry, S. J. Bame, J. T. Gosling and C. T. Russell, Strong electron heating at the earth's bow shock, J. Geophys. Res., in press, 1987.

Winske, D., J. Giacalone, M. F. Thomsen and M. M. Mellott, A comparative study of plasma heating by ion acoustic and modified two stream instabilities at subcritical quasi-perpendicular shocks, J. Geophys. Res., 92, 4411-4422, 1987.

Contributed presentations regarding this work have included:

Fall 1985 AGU Meeting

Mellott, M. M., and E. W. Greenstadt, Subcritical collisionless shock waves: ISEE high resolution plasma wave studies, (abstract), EOS, 66, 331, 1985.

Mellott, M. M., E. W. Greenstadt, and J. D. Scudder, Low Mach number quasiperpendicular bow shocks: Plasma wave profiles and electron heating, (abstract), EOS, 66, 1019, 1985.

Spring 1986 AGU Meeting

Mellott, M M., E. W. Greenstadt, and M. F. Thomsen, The earth's bow shock: Ion acoustic turbulence, electron heating and upstream parameters, (abstract), EOS, 67, 350, 1986.

Fall 1986 AGU Meeting

Greenstadt, E. W., and M. M. Mellott, Plasma wave evidence for reflected ions in front of subcritical shocks: ISEE 1 and 2 observations, (abstract), EOS, 67, 1152, 1986.

Mellott, M. M., and E. W. Greenstadt, Shock-associated plasma waves in the range of the lower hybrid frequency: ISEE observations, (abstract), EOS, 67, 1161, 1986.

Spring 1987 AGU Meeting

Thomsen, M. F., M. M. Mellott, J. A. Stansberry, S. J. Bame, J. T. Gosling, and C. T. Russell, Strong electron heating at the Earth's bow shock, (abstract), EOS, 68, 381, 1987.

Mellott, M. M. and W. A. Livesey, A study of magnetic field strength overshoots in quasiperpendicular bow shocks using averaged field data, (abstract), EOS, 68, 394, 1987.

International Symposium on Collisionless Shocks (Balatonfured, Hungary), June 1987

Mellott, M. M., E. W. Greenstadt, and C. F. Kennel, Plasma waves in the range of the lower hybrid frequency at the terrestrial bow shock.

Mellott, M. M., W. A. Livesey and C. F. Kennel, Magnetic field strength overshoots in quasi-perpendicular bow shocks: Further studies.

Thomsen, M. F., M. M. Mellott, J. A. Stansberry, S. J. Bame, J. T. Gosling, and C. T. Russell, Strong electron heating at the Earth's bow shock.

IAGA Meeting (Vancouver), August 1987

Schwartz, S. J., M. F. Thomsen and M. M. Mellott, Electron heating and the potential jump acorss fast mode shocks.

Mellott, M. M. and E. W. Greenstadt, Plasma waves in the range of the lower-hybrid frequency: ISEE observations at the terrestrial bow shock.

Mellott, M. M., W. A. Livesey and E. W. Greenstadt, Magnetic field strength overshoots in quasi-perpendicular bow shocks: A study using averaged magnetic field data.