PLASMA WAVE SIGNATURES OF COLLISIONLESS SHOCKS AND THE ROLE OF PLASMA WAVE TURBULENCE IN SHOCK FORMATION

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ABSTRACT

We review observations of the plasma waves associated with collisionless shocks, and summarize our understanding of their generation mechanisms and importance to shock physics. The emphasis is on waves generated directly at the shock, especially ion acoustic and lower-hybrid-like modes. The observations are discussed in the context of shock structure, with attention to the distinctions between waves generated in the shock foot and ramp. The behavior of resistive, dispersive and supercritical quasiperpendicular shocks is contrasted. Evidence for the operation of various generation mechanisms, including interactions with cross field currents, gyrating reflected ions and field aligned electron beams, are summarized. The various forms of plasma heating which are actually observed are then outlined and the role of the various wave modes in this heating is discussed. We argue in conclusion that, while plasma wave turbulence may play a vital role in plasma heating for some special shocks, it is of second order importance in most cases.

INTRODUCTION

There are a number of interesting problems that arise in the study of the plasma wave emissions associated with collisionless shocks waves, and we cannot properly discuss all of them here. Rather than present a cursory overview of a great many problems, we have focused instead on one specific issue, namely the role which plasma wave turbulence plays in shock-associated plasma heating. This is a central issue in the classic problem in the study of collisionless shocks, which is the identification of the operative dissipation processes. It has been the standard paradigm for many years now that this dissipation was accomplished via wave-particle interactions. The traditional scenario has been that the cross-field current in the shock ramp drove strong wave turbulence, which in turn responsible for the plasma heating. We will not in this paper attempt to discuss all the wave modes which might conceivably serve as sources for this heating. There already exist a number of excellent papers which discuss these instabilities in exhaustive detail, and to which the reader is referred for further information (1/1 and 2/2 are recent examples). We are concerned here with the question of which instabilities, if any, contribute in a significant way to shock plasma heating. With this goal in mind, we will first survey observations of wave turbulence and plasma heating, and then conclude with a discussion of the relationship between the two.

The discussion will focus on the two general classes of instabilities which have seemed the most promising as sources of shock heating: ion acoustic and lower-hybrid-like modes. The ion acoustic is a high frequency electrostatic mode which preferentially heats electrons and which, at saturation, produces a high energy tail in the ion distribution. The second series of instabilities, which includes the modified two stream, lower hybrid drift and kinetic cross field streaming instabilities, generates electromagnetic waves at frequencies on the order of the lower hybrid frequency, and will be called here collectively the "lower hybrid" modes. They generally produce bulk heating of ion distributions. Early laboratory work seemed well explained by operation of ion acoustic instabilities /3/, as did early bow shock data /4/, but the relative importance of the two modes has not always been clear /5/. This is partly because, until very recently, most of the work done on shock heating consisted primarily of proofs of existence of various modes, and direct connections between the waves and the observed heating were not made.

Fortunately there has been a great deal of recent work on the details of plasma heating in collisionless shocks. Integrating this work with our knowledge of the plasma wave environment of different shocks enables us to go beyond mere observation of the presence of the waves, and to inquire in detail about their role, if any, in shock dynamics. Most of the data on plasma heating has come from studies of the terrestrial bow shock, on which the rest of the paper will, for the most part, focus. Relatively little is known as yet about either
the plasma wave profiles or plasma heating at quasiparallel shocks, and so our discussion will be further limited to quasiperpendicular shocks.

The discussion is organized in terms of a set of shock classes. We will discuss differences and similarities between results for the relatively weak "subcritical" shocks, in which most of the dissipation is produced by resistive and dispersive effects, and stronger "supercritical" shocks where additional dissipation is provided through the reflection of a portion of the incoming solar wind. We will also look for differences between oblique subcritical shocks where dispersive effects dominate, and more nearly perpendicular subcritical shocks where resistive effects become important.

In the first section of the paper we will review observations of ion acoustic and lower-hybrid-like waves as they appear at the terrestrial bow shock, and discuss their sources. The following section reviews observations of ion and electron heating at the bow shock. The paper concludes with a summary which brings together these observations in a discussion of the current evidence for turbulent dissipation in collisionless shock waves.

PLASMA WAVE OBSERVATIONS

It has been clear ever since the flight of the first satellite-borne ELF detectors that collisionless shock waves are accompanied by high levels of plasma wave turbulence /4/. The nature of this turbulence can be seen in Figure 1, which presents electric field data for a crossing of the terrestrial bow shock. The magnetic field magnitude is plotted below for reference. As is generally the case, the crossing is marked by orders of magnitude increase in plasma wave activity in all but the highest frequency channels /6/. Such bursts of broadband noise are in fact associated with a variety of shock-like structures within the heliosphere. These include such diverse phenomena as comets, both natural /7/ and artificial /8/; the AMPTE Li releases /9/; and the edges of diamagnetic solar wind cavities /10/.

The amplitude of the noise varies considerably, but the spectra are remarkably similar from case to case. This can be seen in Figure 2, where spectra from 36 crossings of the earth's bow shock are overlaid. The electric field spectra typically have two components, a broad peak centered between 200 and 800 Hz, and a second component which decreases monotonically with frequency approximately as $f^{-2}$. Magnetic field spectra on the other hand simply decrease with increasing frequency as $f^{-5/3}$. Similar behavior is seen in spectra from other shocks, including other planetary bow shocks /11/, traveling interplanetary shocks.

Fig. 1. Overview of Shock Associated Plasma Waves. Electric field spectral densities associated with a crossing of the terrestrial bow shock are plotted. The magnetic field magnitude is also plotted for reference.
Plasma Waves at Shocks

Fig. 2. Shock Plasma Wave Spectra. Plots of the average magnetic and electric field spectral densities for 36 crossings of the terrestrial bow shock (after /6/).

/12/, and magnetotail slow shocks /13/. Observations of the plasma wave turbulence associated with most of the above mentioned phenomena have only recently become available, however, and one must be cautious in inferring its physical significance. A case in point is the earth's foreshock, which is filled with broadband noise quite similar to that associated with the bow shock itself /14/, but where the underlying physical phenomena are likely to be quite different.

Characteristic plasma wave types can be seen in Figure 1. The narrow band emissions which appear upstream in the 31.1 kHz channel, and abruptly disappear at the shock, are electron plasma oscillations. These emissions, which are locally generated in the upstream region, do not participate in shock formation, and will not be further discussed here. Our focus will be on the mid-frequency (200—800 Hz) electrostatic noise and the lower frequency (10—50 Hz) electromagnetic emissions. These emissions have traditionally been identified as ion acoustic and whistler mode waves /15/.

Ion Acoustic

Profiles of the ion acoustic noise associated with two typical terrestrial bow shock crossings are presented in Figure 3. The electric field intensities in the 562 Hz channel are plotted, in conjunction with a trace of the magnetic field magnitude. The profiles are quite similar in the two cases, which represent subcritical (left panel) and supercritical (right panel) shock crossings. In both cases the ion acoustic noise has several distinct features: It 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 rather quickly to a steady downstream value.

Fig. 3. Profiles of Ion Acoustic Noise. Electric field intensities in peak ion acoustic channels for subcritical (left panel) and supercritical (right panel) terrestrial bow shocks are plotted along with profiles of magnetic field magnitude. Both the wave and magnetic field data have been smoothed.
In the case of the supercritical shock it can be seen that the initial upstream growth is associated with the shock foot, and that the decay to the steady downstream value occurs within the overshoot. The foot and overshoot are both features which signal the presence of reflected gyrating ions, and as such are taken as distinguishing features of supercritical shocks. It thus comes as a surprise to find that plasma wave profiles at subcritical shocks match so precisely those found in supercritical cases. The similarity of the profiles suggests that the same processes are occurring in both cases. Specifically, the ubiquity of the ion acoustic foot suggests that some small number of reflected solar wind ions is present regardless of shock strength (see also /16/ and /17/) and thus calls into question any definition of sub and supercritical which relies solely on the absence or presence of reflected ions as a distinguishing criterion.

The probable generation mechanisms for the various components of shock-associated ion acoustic noise, which are discussed below, are outlined in Table 1. Free energy sources and associated wave modes for both foot and ramp-associated noise are summarized.

Table 1. Ion Acoustic Wave Sources

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<th>EMISSION</th>
<th>FREE ENERGY SOURCE</th>
<th>WAVE MODE</th>
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<tr>
<td>Foot Ion Acoustic</td>
<td>Reflected Ions</td>
<td>Electron Ion Acoustic</td>
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<tr>
<td>Ramp Ion Acoustic</td>
<td>Cross Field Current</td>
<td>Electron Ion Acoustic</td>
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<td>Electron Beams</td>
<td>Electron Ion Acoustic or Electron Acoustic</td>
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The beginning of the growth of the upstream noise is coincident with the forward edge of the reflected ion orbits, and it seems reasonable to assume that the noise is in fact driven by the gyrating reflected ions (see for instance /18/). The operative instability may be either the electron ion acoustic mode, which is driven by the electron-ion core relative drift, or an ion ion instability driven by the relative drift of the two ion components /19/. The electron ion acoustic instability heats electrons rather strongly, and, at saturation, produces a high energy tail in the ion distribution /20/. The ion ion instability on the other hand, can heat the ions directly /21/.

The sharp increase in wave intensities at the front edge of the shock ramp indicates that an additional ramp-associated mechanism also contributes to the ion acoustic amplitudes. The cross-field current has traditionally been invoked as a source for such waves, although a difficulty exists in explaining the generation of ion-acoustic-like noise in the typical bow shock environment, where $T_e/T_i$ is often below threshold. These waves may also be generated by ramp-associated field-aligned electron beams which may drive either electron ion acoustic or electron acoustic modes /22/.

**Lower Hybrid**

The lower hybrid frequency at the terrestrial bow shock is usually ~10 Hz, which is in a difficult measurement regime, often falling in the frequency gap between lowest channel of plasma wave instruments and high frequency cutoff of DC electric and magnetic field experiments. One of the exciting recent developments in shock plasma wave studies is that this frequency range is becoming increasingly accessible. In the last couple of years both the Prognoz-8 ELF instrument /23/, /24/ and the ISEE DC electric field instrument /25/, /26/ have produced data demonstrating the presence of substantial plasma wave turbulence in the lower hybrid frequency range.

Profiles of emissions in the range of the lower hybrid frequency, referenced to the magnetic field profile, are presented in Figure 4. Wave growth generally begins at the front edge of the foot, increases by one or two orders of magnitude at the forward edge of the shock ramp, peaks within the ramp, and then decays to a steady downstream value within the overshoot. Identical patterns are again seen in the plasma wave profiles of subcritical (left panel) and supercritical (right panel) shocks. It seems most likely that the foot-associated emissions are generated by the reflected ion beams and that the ramp-associated noise is driven by the cross-field current. Recent work has shown in fact that the kinetic cross field streaming instability can drive electromagnetic noise in the range of the lower hybrid frequency in both regions /27/, /28/, although there is the difficulty that model foot ion distributions were found to be stable except under low beta conditions.
OBSERVED PLASMA HEATING

Ion Heating

In contrast to laboratory shocks, where strong electron heating and adiabatic ion behavior are characteristic at low Mach numbers /3/, low Mach number bow shocks exhibit little electron heating and strong non-adiabatic ion heating. This was shown in a detailed study of the plasma heating at a series of dispersive terrestrial bow shocks made by Thomsen et al. /17/. In addition to demonstrating strong ion heating at these shocks, the study showed that, while there was some slight upstream heating of the ions, the bulk of the heating occurred within the ramp. The heating extended across the entire distribution, i.e., it was not confined to the creation of a high energy tail, and the primary heating occurred in the direction perpendicular to the magnetic field. In contrast to our detailed knowledge of ion heating in dispersive shocks, we know practically nothing about the ion heating in the more nearly perpendicular subcritical resistive shocks. These shocks are quite rare and as yet little studied.

Our knowledge of the details of the heating at dispersive shocks appears sufficient to allow us to identify the operative instability. As we have seen, there are four distinguishable types of waves observed at these shock crossings: foot- and ramp-associated ion acoustic and lower-hybrid-like noise, each of which could theoretically contribute to the observed plasma heating. The Thomsen et al. study showed, however, that little or no heating occurs in the feet of these shocks, which rules out any important role for any of the foot-associated modes. The same study showed that the primary ion heating is bulk heating in the perpendicular direction, which argues for the operation of lower-hybrid-like instabilities as opposed to ion acoustic type modes. It thus seems most likely that the strong ion heating observed at dispersive shocks results from the operation of a lower-hybrid-like instability.

Electron Heating

Until quite recently it has seemed that little in the way of electron heating would ever be observed in naturally occurring collisionless shock waves. Although very strong electron heating is characteristic in laboratory shocks /3/, electron heating at the earth's bow shock has appeared to be minimal /31/. This has been borne out by recent studies of interplanetary shocks /32/, subcritical bow shocks /17/, and the bow shock in general /33/. The Thomsen et al. study, which investigated the heating at a set of dispersive bow shocks, found that the heating in these shocks could be well accounted for by assuming adiabatic behavior across the magnetic field increase at the shock ramp. They also reported that, although there were indications of some upstream preheating, the electron temperature increase occurred primarily within the shock ramp, and that parallel and perpendicular heating were comparable and generally in phase. Moderately large electron heating is observed in the more nearly perpendicular resistive shocks ($T_e/T_i \approx 10$, /34/). Only two such shocks have so far been identified, however, and little is known about them as yet.
The importance of turbulent effects for electron heating is less clear in the case of supercritical shocks. In one case, studied in exhaustive detail by Scudder et al. /35/, observed distributions were compared with model distributions predicted on the basis of interaction with shock's macroscopic fields, and good agreement was found. Scudder et al. therefore concluded that the reversible forces associated with the shock's DC electric and magnetic fields were primarily responsible for increasing the electron temperature across the shock, and that wave-particle interactions participated in the process only in a second order fashion.

In an alternative scenario, on the other hand, Moses et al. /36/ and /37/ have proposed that an electron ion acoustic instability driven by reflected gyrating ions may be responsible for the strong electron heating observed at the Jovian bow shock. Interestingly enough, their calculations also suggest that, because of differences in the plasma characteristics, negligible heating should result from operation of this instability at the earth.

Scudder et al.'s /35/ work, in combination with the results of earlier surveys which showed minimal electron heating, indicates little need for the invocation of turbulent effects in electron heating at the terrestrial bow shock, except in the case of the two resistive shocks. It has however been recently established that there are in fact a significant number of terrestrial bow shock crossings in which strong electron heating (factors of 20-25) can be observed /38/. The heating occurs under a variety of conditions and shows no particular parameter dependence. Its source is as yet undetermined.

**CONCLUSIONS**

Strong plasma wave turbulence is observed in association with a wide variety of shock and shock-like phenomena in the heliosphere. The emissions fall in two major classes, mid-frequency electrostatic ion acoustic waves and lower frequency electromagnetic lower-hybrid-like emissions. Growth in both types of emissions begins at the forward edge of reflected ion orbits, and rises abruptly at the front of the shock ramp. The free energy sources driving emissions in the two regions are most likely to be, in the foot, the gyrating ion beam resulting from the reflection process, and, in the ramp, the cross-field current. The ion acoustic noise associated with the ramp may alternatively be driven by field aligned electron beams. Either or both of the electron ion acoustic and ion ion acoustic instabilities may be operating in the shock foot. The operation of the kinetic cross field streaming instability can probably explain the presence of lower-hybrid-like waves in both the foot and ramp. An increased appreciation for the possible role of lower-hybrid-like instabilities in shock associated heating has been one of the important advances which has recently taken place in our understanding of shock physics. A second important change has been the appreciation of the possible importance of foot associated turbulence driven by gyrating reflected ions as opposed to the ramp-associated current-driven modes.

While the sources of observed waves seem relatively clear, our understanding of their effects on the plasma is much less so. The mechanisms inferred to operate in plasma heating at the terrestrial bow shock are summarized in Table 2. Turbulence appears required to explain the heating only in a few special cases: ions in subcritical shocks, electrons in two resistive shocks, and electrons in a subset of supercritical shocks. It seems probable that we understand the ion heating in subcritical shocks, which most likely results from a kinetic cross field streaming instability driven by the ramp current. The source(s) of the anomalous electron heating in the resistive and supercritical shocks is as yet undetermined. It remains possible that turbulent mechanisms may play a larger role in the dissipation in shock and shock-like phenomena other than the terrestrial bow shock. It will be necessary however to

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<tr>
<th>SPECIES</th>
<th>MECHANISM</th>
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<tr>
<td>IONS in Dispersive Shocks</td>
<td>Lower hybrid turbulence</td>
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<td>IONS in Supercritical Shocks</td>
<td>Reflection and gyration</td>
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<td>ELECTRONS in Resistive Shocks</td>
<td>Unknown turbulent mechanism</td>
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<tr>
<td>ELECTRONS in Dispersive Shocks</td>
<td>Magnetic field compression</td>
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<tr>
<td>ELECTRONS in Supercritical Shocks</td>
<td>Interaction with potential, possible turbulent heating in some cases</td>
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obtain better data on the characteristics of the plasma heating in these cases before the relative roles of macroscopic and microscopic processes in these phenomena can be assessed.

ACKNOWLEDGMENTS

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38. M. F. Thomsen, private communication (1986).