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A Collisionless Shock Wave Experiment

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Abstract

Collisionless shock waves are a very important heating mechanism for plasmas and are commonly found in space and astrophysical environments. Collisionless shocks were studied in the laboratory more than 20 years ago, and more recently in space via *in situ* satellite measurements. We propose a new laboratory shock wave experiment to address unresolved issues related to the differences in the partition of plasma heating between electrons and ions in space and laboratory plasmas, which can have important implications for a number of physical systems.

Introduction

Collisionless shock waves (CSW) and magnetic reconnection are the two most important mechanisms by which energy in converted from one form to another in a plasma. Through reconnection, energy stored in the magnetic field is converted to particle kinetic energy, while CSW convert particle streaming energy into thermal motion. CSW occur throughout the universe: in supernova remnants, in solar flares, and at bow shocks upstream of planets and comets. The effects of CSW were observed in high altitude nuclear tests conducted in the early 60's. CSW were also used in the early days of the magnetic fusion program to produce hot (keV) temperature plasmas. Laboratory experiments to study the fundamentals of CSW were carried out in the late 60's and early 70's. Later, more detailed properties of CSW were inferred from spacecraft measurements at the Earth's bow shock and from numerical simulations. These later studies yielded some results that were contrary to the laboratory experiments. However, no follow-up lab experiments have been conducted in the last 20 years to attempt to reconcile these differences or to reexamine CSW under more modern laboratory conditions. Here we propose such an experiment, which could be done using the Colt capacitor bank at Los Alamos. In this report, we briefly review research on CSW over the past 30 years and discuss the important unresolved issues that the experiment will address. We also describe the basic setup of the experiment and show representative numerical calculations to model it.

Historical Perspective

Research on CSW can be divided into two periods: "The First Golden Age of Collisionless Shocks", from roughly 1964 to 1974, and the "Second Golden Age" from 1979 to 1989 (the quotes are those of Kennel [1]). While fluid shocks were well understood for many years, it was not until the late 50's that Sagdeev [2] proposed that a shock could be formed in a collisionless plasma with the shock transition occurring over a scale length much less then that due to binary collisions. This concept was verified when the IMP-1 spacecraft detected the Earth's bow shock, which forms in the high speed solar wind upstream of the Earth's magnetosphere [3]. Typically, the width of the bow shock is about 100-1000 km, much less than the binary collision mean free path in the solar wind (typically 10^6 km). CSW were also thought to form after nuclear explosions very high in the atmosphere, and much effort went into understanding the consequences of energetic particle deposition in and the resultant heating of the lower atmosphere following these bursts. A few years later, a number of laboratory experiments [4-9] were carried out to study the properties of CSW (see [10] for a review). Most of these experiments were based on the theta-pinch concept, with an azimuthal electric field imposed by an externally wound coil which produces a fast rising magnetic field at the wall that propagates inward (the magnetic piston), driving a shock ahead of it. These shocks were characterized by the Alfven Mach number (ratio of the speed of the upstream flow relative to the shock to the Alfven speed based on the upstream parameters) in the range $M_A = 2\text{-}20$ and angle between the magnetic field direction upstream of the shock and the shock normal, Θ_{nB}, mostly at 90^o (a so-called perpendicular shock). An example of some experimental results is displayed in Figure 1. Typically, it was found that most of the heating at the shock occurred in the electrons. That heating was far above what was expected from adiabatic compression and was termed "anomalous". At higher Mach numbers, more of the heating went into the ions. Much effort went into trying to understand the fundamental plasma processes that caused the heating. It was found that short wavelength plasma instabilities in the shock front generate microscopic electric fields that heat the plasma and provide the very short collisional scale that allows the shock to form (see Biskamp for a good review [11]). In addition, a number of computer simulations were carried out to understand the properties of the instabilities and the formation of CSW [12-14].

The "Second Golden Age" began with the launch of the International Sun Earth Explorer (ISEE) satellites. Two of these satellites were in orbit close to the Earth and made many crossings of the bow shock. The satellites were closely space (few 1000 km apart), allowing accurate measurements of the thickness of the shock. The third satellite, ISEE-3, was upstream of the Earth in the solar wind and measured properties of interplanetary shocks. The AGU monographs [1,15] provide detailed articles about the results of the mission concerning CSW up to 1984. More recent work is summarized in [16]. While the satellites provided shock properties under variety of upstream conditions (M_{A}, Θ_{Bn}), the variability of the solar wind meant that conditions were not controllable or reproducible. In addition, during the 80's the development of more sophisticated simulation techniques, so-called hybrid codes in which the ions are treated as individual particles and the electrons as a massless fluid, allowed detailed comparisons with observations [17] and were able to demonstrate that most of the structure of CSW in space could be related to the various characteristic scales associated with the dynamics of the ions, as shown in Figure 2. During this period, there was also a major conceptual breakthrough in understanding how electrons are heated at shocks in space. Contrary to the laboratory experiments, the electrons at shocks in space are heated only very weakly [19], i.e., not much above adiabatic compression. According to the work of Goodrich and Scudder [20] and others, the major contribution to electron heating was due to the electron response to the electrostatic potential jump across the shock, with plasma instabilities playing only a secondary role.

Issues

Thus, in comparing CSW in the laboratory and in space, a major discrepancy stands out at once: In the laboratory, there is almost always strong electron heating, while in space the electrons are heated only slightly. Some of this difference is due to the fact that CSW in space are usually at higher Mach number, and it is known from the laboratory experiments that ion heating becomes more important relative to electron heating in that case [7]. However, only weak electron heating also occurs at interplanetary shocks [21], where the Mach number is much lower. Some of the disagreement can probably be attributed to the fact that CSW in space occur at oblique angles, whereas the laboratory shocks were almost all perpendicular shocks. But a more significant feature might be that shocks in space are essentially steady state, whereas the laboratory shocks are still evolving and may not have reached their final state. This evolutionary nature can be important in a number of applications, such as supernova explosions and solar flares as well as in high altitude nuclear bursts. In such cases, the partition of energy behind the shock between electrons and ions is an important question. In the astrophysical context, it is only the electron energy that can be inferred from observations, and the strong xray emission that is detected remains a puzzle [22]. In solar flares, the energetic particle data place severe constraints on how the electrons and ions are heated [23]. In high altitude bursts, the electron temperature is the determining factor in chemical processes involving the heated atmosphere. In these cases the shock formation process and its relation to the driving magnetic piston can thus play a potential key role in determining the dissipation mechanism, and hence the energy partition, as well as the evolution of the shock structure. This issue is also expected to be important in our proposed experiment.

Proposed Experiment

Our proposed experiment is based on the well-known concept of theta-pinch compression to make an imploding magnetic field that produces a radially propagating shock. A crude first design uses parameters similar to those of the Implosion Heating Experiment (IHX) [24], an experiment fielded by the magnetic fusion (CTR) division at Los Alamos in the mid 70's. The purpose of that experiment was to investigate the implosion process and the plasma heating mechanisms, as part of a larger program to study the feasibility of fusion based on the theta-pinch concept. The experiment used a fast rising magnetic field to generate a very high Mach number shock wave and a rather large chamber (40cm diameter) to allow a long implosion phase. Typically, the initial ion density was $\sim 4 \times 10^{14}$ cm^{-3} embedded in a magnetic field of about 75 Gauss. The applied electric field produced a magnetic field of about 5 kG at the wall. The implosion generated a shock with speed of about 2×10^{7} cm/s, implying a Mach number of about 35, based on the initial density and magnetic field. The one-dimensional hybrid code, AURORA [25], was used to model the IHX experiments. The left side of Figure 3 displays the results of one calculation, showing radial profiles at $t=0.5\mu s$ of the magnetic field, the ion density, the electron temperature, and ion v_r-r phase space. One sees a well formed shock at $r \sim 12$ cm, with a jump in the magnetic field, density, and electron temperature. Ahead of the main shock ramp is the well-known "magnetic foot", which from the phase space plot is clearly seen to be related to the reflection of a significant number of ions at the shock front. The fact that these ions have not yet had time to return to the shock and contribute to the downstream heating suggests why electron heating can be so dominant at this time in the experiment.

To be meaningful for comparison with CSW in space (e.g., Fig. 2), the proposed experiment must satisfy two criteria: (1) the Mach number should be greater than about 3 so that there is some dissipation due to ions reflected at the shock, and (2) the reflected ions have time to gyrate back into the downstream and contribute to the overall heating. Using the above IHX calculations as a guide, it is evident that to satisfy these criteria in this system, the bias magnetic field must be increased about a factor of 10. The plots on the right side of Fig. 3 correspond to a case with a bias field of 750 Gauss. One sees that the reflected ions do gyrate downstream and since the shock speed is about the same, the Mach number is indeed much lower, $M_A \sim 3.5$. With these calculations as a basis, AURORA can then be used to optimize the design of the experiment, taking into account the electrical connection to the capacitor bank. We propose to do a series of experiments varying the initial plasma fill density and the bias magnetic field to study the electron heating as a function of Mach number and the degree to which the reflected ions return to the shock. In order to measure properties of the shock and the electron heating, magnetic field probes and Thomson scattering will be used. It is hoped that the probe measurements will also be able to determine the formation time of the shock, which is another issue that is not well understood at present.

Two aspects of these calculations used to model the experiment should be noted. First, the hybrid algorithm is not very good for calculating the electron temperature behind the shock, which of course is the quantity that we would most like to determine. AURORA uses a phenomenological model for the anomalous resistivity; a model for the resistivity based on the microphysics of possible cross-field instabilities is also available [26], but it also involves a number of assumptions. These models have been benchmarked with other experimental results, so there is some confidence in their use, but they are to be applied with caution when designing new experiments. The second issue concerns two-dimensional effects that are not included in AURORA. We are in the process of modifying the electromagnetic particle code ISIS to do implosion calculations with massless, fluid electrons [27]. Such calculations will be able to assess the importance of particle endloss and the non uniformity of the shock along the length of the column.

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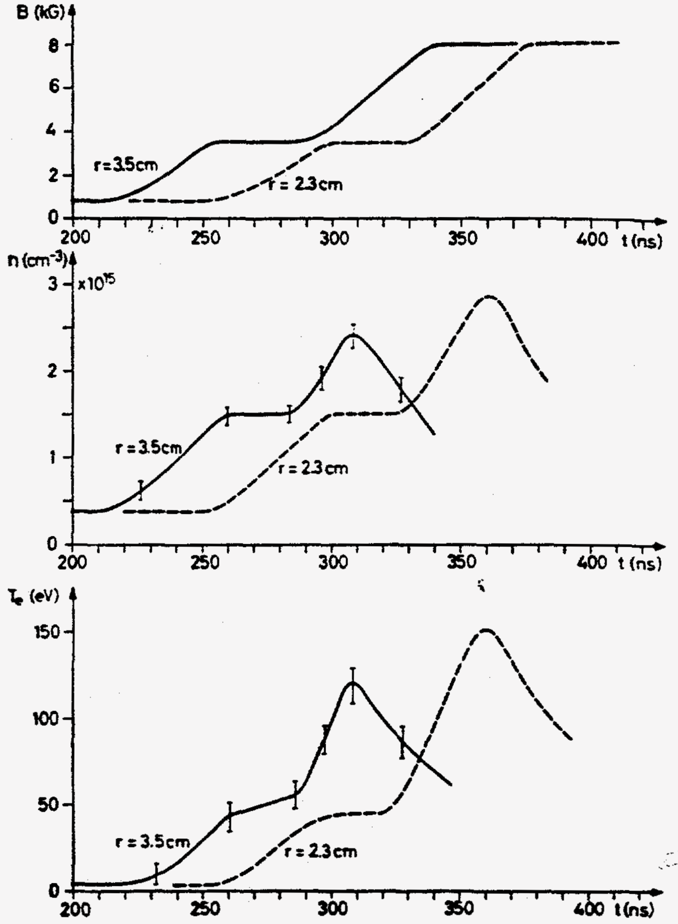

Fig. 1. Variation in magnetic field (B), density (n) and electron temperature (Te) as a function of time at two probe positions showing CSW, from experiments in [5].

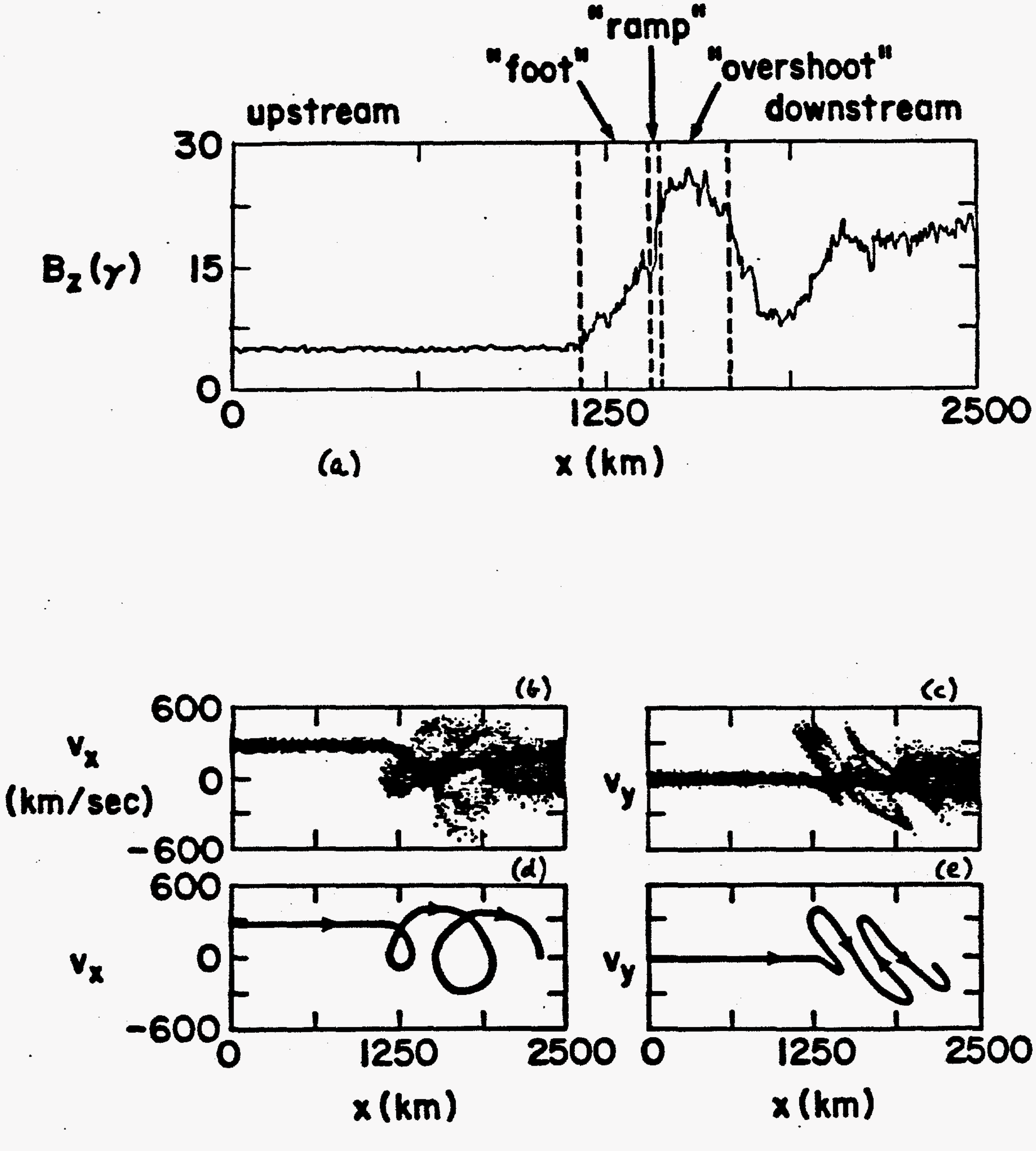

Fig. 2. Magnetic field profile of a bow shock crossing from a hybrid simulation, showing scale features and their association with ion dynamics in the calculations [18].

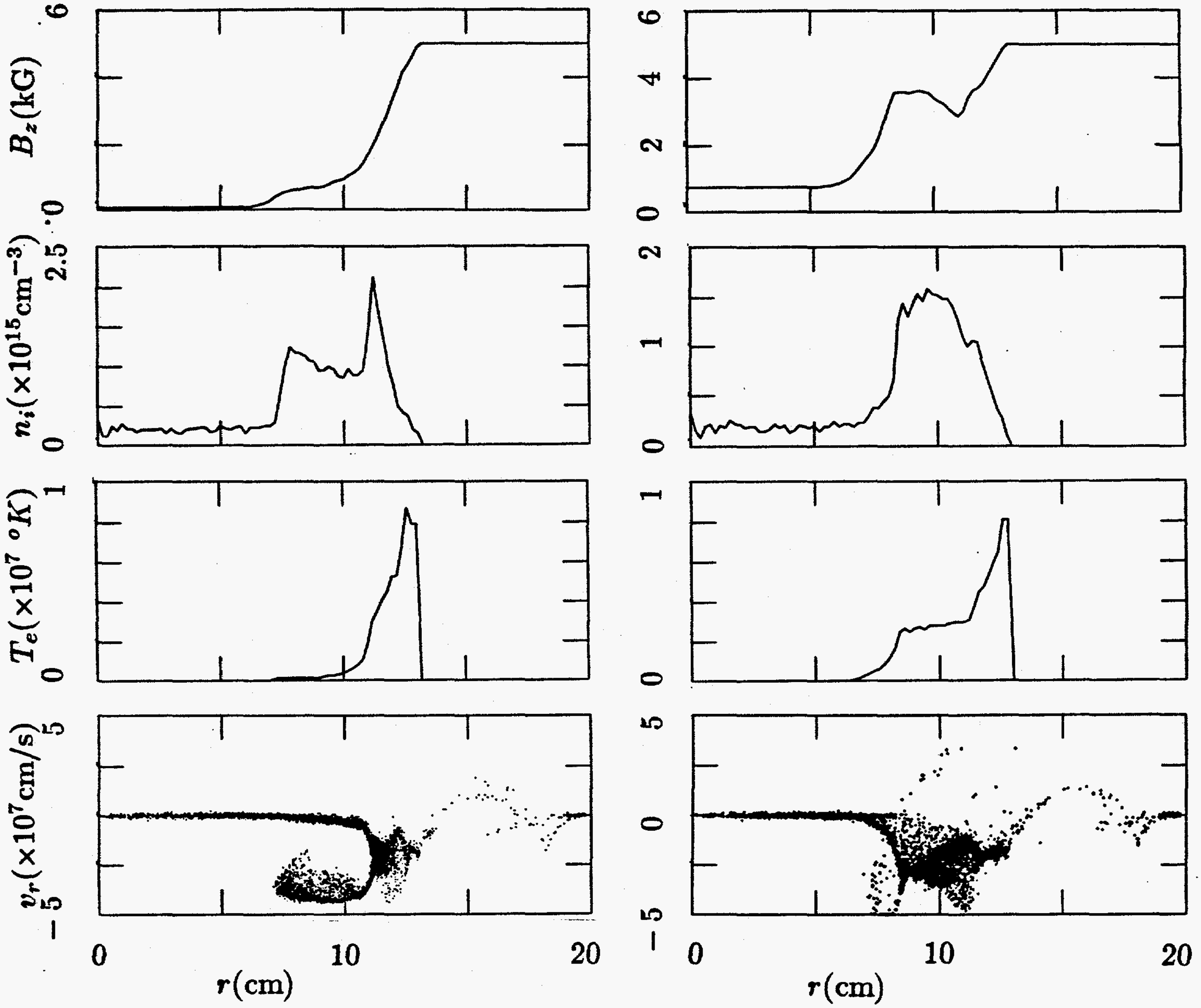

Fig. 3. Results of AURORA simulations showing profiles of the magnetic field, ion density, electron temperature and ion v_r-r phase space at 0.5μs for two runs: (left) IHX parameters [25]; (right) with stronger bias field.