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VERY HIGH MACH NUMBER SHOCKS: THEORY

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ABSTRACT

The theory and simulation of collisionless perpendicular supercritical shock structure is reviewed, with major emphasis on recent research results. The primary tool of investigation is the hybrid simulation method, in which the Newtonian orbits of a large number of ion macroparticles are followed numerically, and in which the electrons are treated as a charge neutralizing fluid. The principal results to be presented are (1) electron resistivity is not required to explain the observed quasi-stationarity of the earth's bow shock, (2) the structure of the perpendicular shock at very high Mach numbers ($M_A \simeq 15-20$ and $\beta \simeq 1$, where M_A is the Alfvén Mach number of the shock and β is the ratio of the thermal to magnetic pressure) depends sensitively on the upstream β and electron resistivity, (3) two-dimensional turbulence will become increasingly important as the Mach number is increased, and (4) non-adiabatic bulk electron heating will result when a thermal electron cannot complete a gyro-orbit while transiting the shock.

INTRODUCTION

In the early 1980's, a significant increase in our understanding of perpendicular collisionless shock structure resulted from analysis of the ISEE (International Sun-Earth Explorer) data and from analytic and from numerical modeling efforts. It was found that when the plasma flow direction ahead of the shock is nearly perpendicular to the local magnetic direction (hence, a perpendicular or quasi-perpendicular shock) and when the mean free path for Coulomb collisions is much larger than the mean shock thickness, as exists in the solar wind, then for sufficiently large values of the ratio of the shock speed to the upstream Alfvén speed (the Mach number M_A), ion reflection is the principal source of dissipation.

The criterion for the onset of the reflection of ions is called the first critical Mach number M^* /1/, and is due to the fact that for sufficiently high Mach numbers neither anomalous resistivity nor electron dispersion can prevent the shock from steepening (see, for example, discussions in /2/). A form of ion "viscosity" results when the shock speed exceeds the Alfvén Mach number M^*, and a fraction of the incoming ions at the shock are specularly reflected by a combination of electric and magnetic forces /3,4/. These ions gyrate upstream of the shock and gain energy because of their motion in the direction of the convection generated electric field. When these ions re-intersect the shock and gyrate on downstream, they share their acquired energy with the directly transmitted ions via the electromagnetic Alfvén Ion Cyclotron instability /5,6/, completing the dissipation process.

For average solar wind conditions near earth orbit /7/, $M^* \simeq 3$. Since the typical Alfvén Mach number of the solar wind flow relative to the earth is $\simeq 5-6$, the bow shock is excellent for testing theories and simulations of supercritical quasi-perpendicular shock structure. The major prediction of the theories /1,2,8,9,10,11/, that a fraction of the incident ions are specularly reflected at the shock has been verified in several observational studies /12,13,14/. The associated magnetic field structure, which consists of a magnetic "foot" which scales as the shock speed, and of a thin magnetic ramp and overshoot, is in qualitative agreement with the predictions of theory and simulation /15/. Other details, such as the form of the electron distribution function through the shock and the final downstream isotropization of the ions is in a more preliminary state of comparison.

In this paper recent theoretical advances in perpendicular shock physics will be examined. Attempts to extend the existing shock models to extreme plasma regimes which are unlikely to be found near the earth but may exist astrophysically will be reviewed. It is shown that while such shocks do exist and have scalings similar to those found at lower Mach numbers, the stability and time-stationarity of these shocks depends sensitively on a combination of the Mach number, upstream ion beta, and resistivity. Full particle simulations of perpendicular shocks are examined and their relevance to the earth's bow shock is discussed. Particular attention is paid to the claim that explicit charge separation effects need to be included for a theoretical description of perpendicular shocks to be correct. Finally, two-dimensional shock studies and electron heating at high Mach numbers will be reviewed.

SIMULATION MODELS

The simulation results in this paper are primarily those generated by a one or two dimensional, electromagnetic hybrid code. The ions are treated as individual macroparticles and pushed in time and space by numerically solving Newton's Law. The electrons are treated as a massless fluid and can be either resistive or isentropic. The electron fluid variables are advanced in time on an Eulerian grid by solving a set of fluid moment equations. Quasi-neutrality is imposed, so that the electron density is always set equal to the ion density within each spatial cell. A given time step consists of advancing the ions in the (previously) determined fields, then using the updated ion density and currents in conjunction with Maxwell's equations to determine the new electron fluid variables and fields. More details of the various numerical ways of obtaining the solutions to these equations can be found in /16,17/, and will not be repeated here.

A second simulation model whose results will be discussed is the explicit full particle code. In this model both the electrons and ions are treated as macroparticles, so both full electron dynamics and explicit charge separation effects are retained. A limitation of this method is that because of constraints on the size of the time step and spatial cell size, the number of upstream ion gyroperiods the simulation can be run and the size of the system in upstream ion inertial lengths is quite small.

BOW SHOCK SIMULATIONS

There have been two studies of collisionless perpendicular shocks in the last few years /18,19/ using explicit full particle codes. The goal has been to extend earlier simulation results, and to study more closely the physical distinctions between hybrid simulation models, which assume quasi-neutrality, and the full particle codes which include electron kinetic and charge separation effects. The authors of /18,19/ conclude that while the two models are superficially similar, there are important differences. In the one-dimensional full particle simulations, the shock periodically breaks and reforms, and dissipation is due to trapping of the ions followed by a $\vec{V} \times \vec{B}$ acceleration and de-trapping. By contrast, simulations using hybrid codes of shocks with similar Mach numbers are quite steady, showing no tendency to wavebreak and overturn /20/. A likely source of the discrepancy is the assumption of charge neutrality in the hybrid codes, since in the full particle simulations a charge difference of 10 to 30% is observed within the shock ramp /19/. The problem is complicated, however, by the fact that in the full particle simulations the ratio of the upstream plasma frequency to electron gyrofrequency ω_{pe}/ω_{ce} is not very large, between 1 to 10. This ratio cannot be made much larger because of computational constraints, and is much smaller than that observed upstream of the earth's bow shock, between 1000 to 10000. Using simple scaling arguments, Quest /20/ has shown that as ω_{pe}/ω_{ce} is increased the amount of charge separation expected in a shock ramp of fixed thickness decreases. Thus, while charge separation and its associated effects are expected in the full particle simulations, the earth's bow shock with the solar wind's much larger ω_{pe}/ω_{ce} should force quasi-neutrality.

Another result of relevance to the earth's bow shock is the demonstration by numerical simulation that steady shock solutions are possible even in the absence of resistivity /20/. In Figure 1 a hybrid simulation of the November 7th, 1977 shock is displayed. This nearly perpendicular ($\theta_{Bn} = 82°$) high Mach number ($M_A \approx 8$) shock has been analysed in great detail by Scudder et al. /21/. The ion phase space, magnetic field ramp, and electrostatic potential structure is quite similar to previous simulation results, with one important difference. In this particular algorithm, the electrons were assumed to behave isentropically, with a ratio of heat capacities set to 5/3. Prior authors had maintained that for a time-stationary shock solution resistivity was needed in the electron energy equation /10,22/. The observed stationarity of the bow shock shock was thus argued to be the consequence of the presence of anomalous resistivity. While the present result does not exclude the contention that resistivity is present at the quasi-perpendicular bow shock, it does demonstrate that resistivity need not be invoked to explain the observed time stationarity.

VERY HIGH MACH NUMBER SHOCKS

While a great body of information has been accumulated about the structure of collisionless shocks in

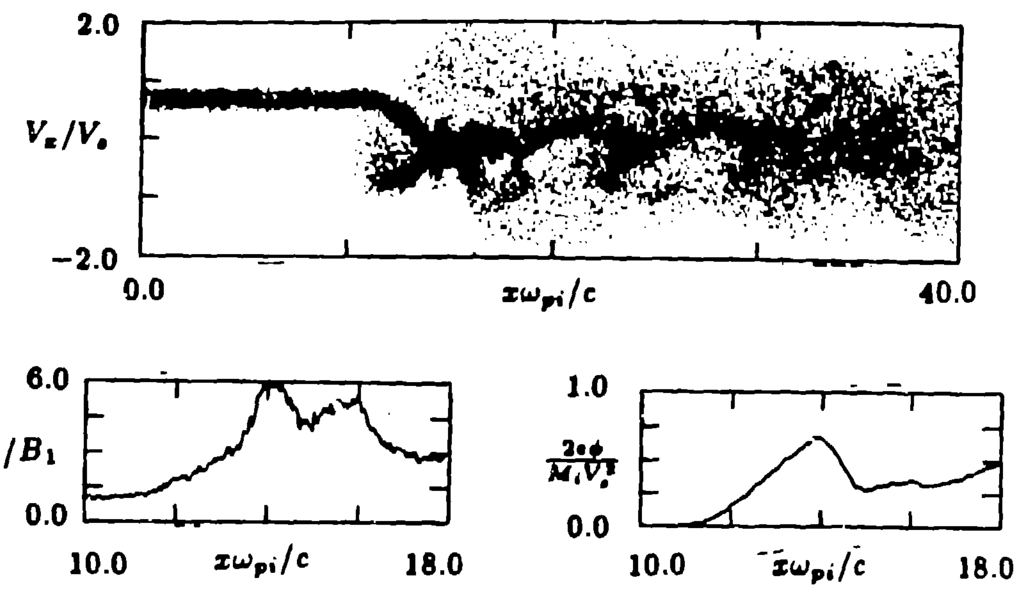

Fig. 1. Hybrid simulation of the Nov 7th, 1977 shock observed by ISEE /20/. The ion phase space in the shock normal direction normalised to the shock speed (V_x/V_s) is plotted vs position normalised to the upstream ion inertial length ($x\omega_{pi}/c$). The magnetic field normalised to the upstream field (B/B_1) and the electrostatic potential in the shock normal direction normalised to the shock ram energy ($2e\phi/M_iV_s^2$) is also plotted against position.

the near earth environment, relatively little is known about shocks in the outer solar system and even less about astrophysical shock structure in other parts of the galaxy. The difficulty is that a large data base generated by "in situ" measurements of the shock is only available for the earth's bow shock. The data bases for the bow shocks of the other planets and for shocks in the solar wind is far less complete, while astrophysically, all we know must be gleaned from measurements by earth-based telescopes. In the case of the outer solar system, we do know that shocks with estimated magnetosonic Mach numbers M_{ms}, between 12 and 20 do exist /7,23/, while astrophysically spherical shock waves with $M_{ms} \approx 1000$ have been inferred from electron temperature measurements of super-nova remnants /24/. In Figure 2 the magnetic field signature of an outbound Jovian bow shock crossing by Voyager 1 is displayed /7/. The estimated magnetosonic Mach number is 12 and the estimated upstream β is 3. The magnetic signature

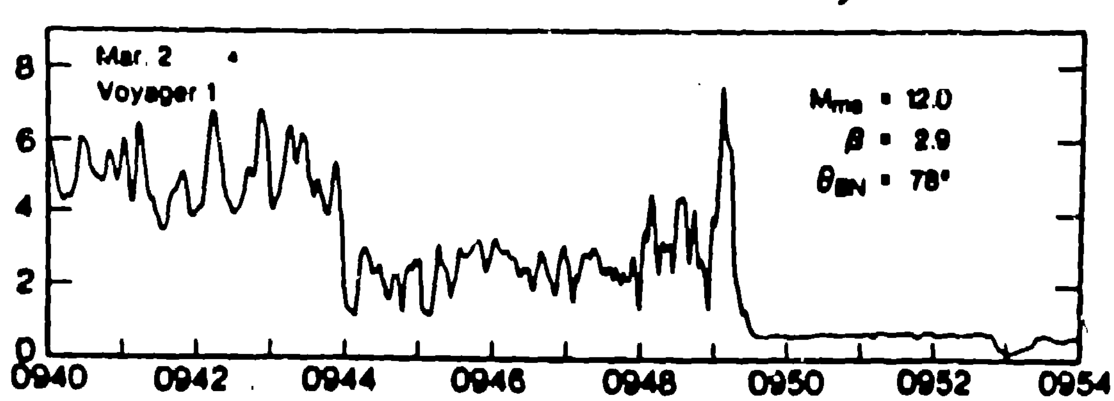

Fig. 2. Magnetic field profile of a high Mach number Jovian quasi-perpendicular bow shock from an outbound pass by Voyager 1. From /7/. The magnetic field in gammas is plotted vs universal time in hours and minutes.

is similar to that seen at the earth's perpendicular bow shock, although the magnitude of the overshoot is far larger at Jupiter.

Given the success of the hybrid simulation codes in reproducing the general features of the earth's bow shock, it is a natural temptation to run the codes for the extreme plasma parameters expected in the outer solar system and astrophysically. The results can be used to predict the structure of these shocks and to compare with whatever data are available. In Figure 3 the ion phase space is plotted for a hybrid simulation of a $\beta = 1$ shock with $M_A = 22$ /25/. The electron diffusion length is set less than the cell size, so the electron behavior is approximately isentropic. The ion phase space is plotted as a function of position within the simulation box at four different times, roughly $0.1\Omega_{ci}^{-1}$ apart, where Ω_{ci} is the upstream ion gyrofrequency. The shock behavior is unsteady, but cyclic, steepening up for part of the cycle then overturning in phase space, resulting in a mixed, heated plasma. The cycle time is approximately $2.0-4.0\Omega_{ci}^{-1}$, and can be characterised by a period of total ion reflection followed by none, the aggregate resulting in the proper amount of heating downstream of the shock necessary to satisfy the Rankine-Hugoniot relations. When the resistive diffusion length is set greater than the cell size, with the other parameters set the same as in the preceding example, the shock structure is very different. The results are quite similar to earlier simulation results at lower Mach numbers /10/, in that the structure is quite steady and consists of a well defined magnetic foot and ramp, and a fraction of the incident ions are specularly reflected. It is clear, therefore, that within the hybrid description of perpendicular shocks, there is a dependence of the shock structure on the magnitude of the electron resistivity.

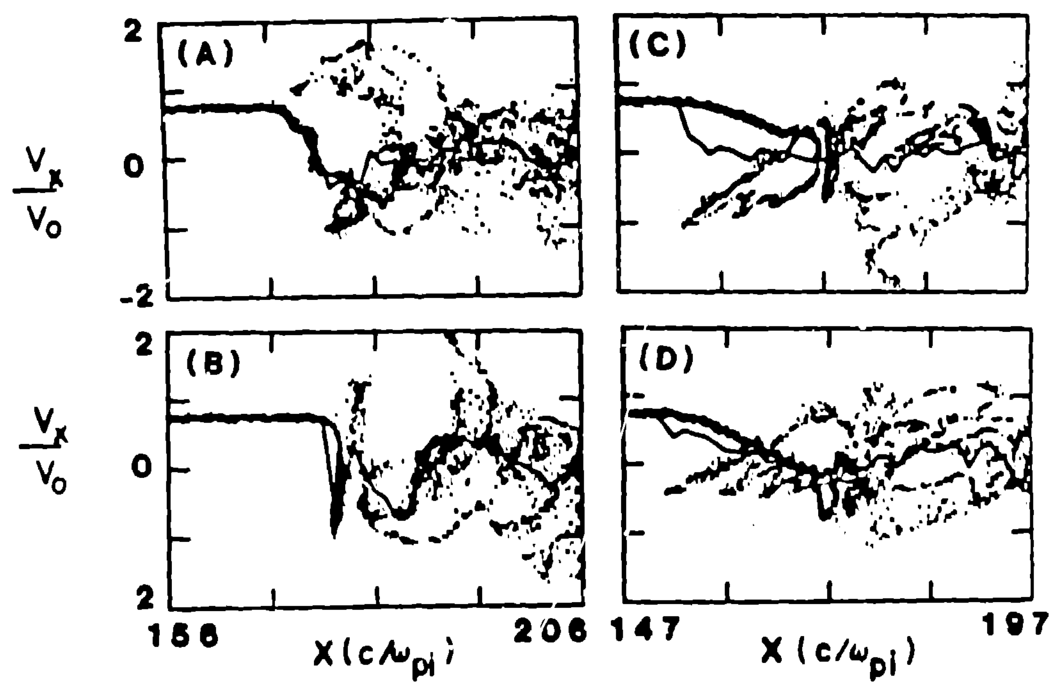

Fig. 3. Ion phase space at 4 different times for $M_A = 22$ and $\beta = 1$. perpendicular shock simulated by one dimensional hybrid code /26/. The ion velocities normalised to the shock speed V_x/V_0 are plotted against the shock position normalised to the upstream ion inertial length $x(c/\omega_{pi})$.

More recently, a parametric study of perpendicular shocks using a one dimensional hybrid code was done over a wide range of Mach numbers /26/. It was found that shock stability depends on three parameters, Mach number, upstream ion β, and resistivity. For moderate β plasmas, quasi-stationary shock solutions are possible with or without resistivity up to approximately $M_A = 15$. For higher Mach numbers, a finite resistivity is necessary in order to stabilise the shock. When the upstream β is lower, however, previous studies have shown that the transition to overturning shock structures occurs at smaller Mach numbers /10/. There have been several attempts to explain the high Mach behavior, although like the simulation results, the theories should be considered tentative at best. Papadopoulos /27/ and Goodrich /28/ have suggested that the ion sonic Mach number is critical in controlling the shock, because as the

Mach number increases, the spread in energy of the upstream ion beam normalised the total ion energy decreases. At sufficiently high Mach numbers it is no longer possible to maintain a steady ion reflection rate, and an unsteady shock results. Kennel et al. /2/ suggest that the overturning may be explainable in terms of a new critical Mach number, at which point the modified linear compressive perturbations just downstream of the magnetic overshoot can overtake the shock, and as a consequence overturn it. A similar idea has been proposed by Krasnosel'skikh /29/, who argues that singularities in the density gradients ("gradient catastrophe") are a prevalent feature of the high Mach shock analytic solutions, and results in a "flickering" of the shock structure on ion cyclotron timescales.

TWO-DIMENSIONAL EFFECTS AND ELECTRON HEATING

In the preceding studies, the shock has been assumed to be a function of a single spatial variable, the shock normal direction. At high Mach numbers, however, the energization of the reflected ions results in a bimodal downstream distribution in which the energy in the direction perpendicular to the magnetic field far exceeds that in the parallel. This type of distribution is unstable to the the generation of ion cyclotron waves propagating in the direction of the magnetic field, which act to reduce the temperature anisotropy and to partition the total energy between the two ion components. Two-dimensional hybrid simulations by Thomas and Brecht /30/ have verified the existence of this turbulence and have shown that the spatial scale over which the waves amplify can be on the order of $\sim c/\omega_{pi}$. Thus, at very high Mach numbers the periodic oscillations seen in the one-dimensional solutions will be replaced by turbulent oscillations with a correlation time of $\sim \Omega_{ci}^{-1}$.

At very high Mach numbers the assumptions used to describe the electrons in the hybrid simulation codes need to be re-examined to see if they are still valid. In particular, the assumption of massless electrons and that of charge neutrality may no longer be correct. Increasing the Mach number of the shock results in an increased potential jump, and as a consequence, an increase in the distance over which an electron completes a gyro-orbit within the shock. If M_A exceeds $L\omega_{pe}/c$, where L is the distance over which the electrostatic potential rises, then the electrons cannot conserve their adiabatic invariant, and energization results /31/. Explicit particle simulations have shown that as the above criterion is exceeded, the electrons are strongly heated /31/. It is even possible that as the Mach number continues to increase, the electron heating will dominate over the ions, resulting in elimination of reflected ions at extreme Mach numbers /32/. Whether or not this will occur will depend on the distance over which the potential jump occurs. Full particle simulations of such high Mach number shocks are at present prohibitively expensive, and will have to await a future generation of computer or more efficient computational algorithm. Finally, since charge separation effects scale as the Mach number of the shock /20/, full particle studies are needed to determine when and under what conditions these effects strongly modify the high Mach number shock structure.

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