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TITLE HYBRID SIMULATIONS OF A CURVED SHOCK

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Hybrid Simulations of a Curved Shock

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Calculations of supersonic flow past magnetized and unmagnetized objects have been used to model the properties of shock waves associated with the flow of solar wind past the planets. Such calculations have been performed both in the fluid limit (Spreiter and Stahara, 1985) and in the MHD limit (Walker and Ogino, 1989 and the references therein) in both two and three dimensions.

Even though such calculations do give some properties of the interaction, the basic shock dissipation mechanisms are not retained. On the other hand, idealized planar calculations have been performed with full particle codes and hybrid (particle ions and massless fluid electrons) codes to examine the shock dissipations processes. For the usual planetary case of supercrital flow relative to the Alfven velocity ($V_{flow} > 3V_A$), the dissipation mechanism involves the reflection of part of the incoming ion population, a process well modeled by hybrid simulations. Hybrid simulations of planar shock waves have also yielded much information concerning the electromagnetic field structure of the shock. (Goodrich, 1985).

Unfortunately, the planar calculations do not include all of the processes thought to be important in the global structure of the bow shock. Among these processes are the nonlocal transport of reflected ions though the shock, and the question of which ions make up the foreshock population, i.e., those ions that travel back upstream into the solar wind from the quasiparallel portion of the shock. To answer these questions, a self consistent approach that includes ion kinetic phenomena together with global shock phenomena is needed. Here we attempt to examine these issues by performing large scale hybrid simulations of a curved shock in two dimensions.

Many algorithms are available for solving the electromagnetic fields in hybrid codes in 2-D, e.g., Harned (1982), Terasawa (1986), and Quest (1989). The method we use is an adaptation of the later two methods. The difference between the methods is the manner in which J_i^{n+1} is calculated from B^{n+1}, $J_i^{n+1/2}$, and $E^{n+1/2}$, where J_i is the ion current density, B is the magnetic field, E is the electric field, and the superscript n is the time step level. In Terasawa's method, a second order Runge Kutta intergration is used to predict the desired quantity; repeated iteration is possible, if desired. In Quest's approach, the fluid equations are used to calculate the desired quantity. Using the fluid equations yields an algorithm that is more robust than that of Terasawa. Unfortunately, the algorithm requires separate fluid equation predictions for each species, and the form of the required equations is complicated if more than one charge to mass ratio is being simulated. Another approach is to extrapolate J_i^{n+1} from its value at the previous time step and previous half time step. Many properties of this algorithm are satisfactory, including the possibility of including species with different charge to mass ratios. We performed the global hybrid simulations using this method.

For the initial calculations we chose a two dimensional model with the ambient magnetic field in the plane of the simulation, making an angle of 60^0 with respect to the incoming flow velocity. Only the front edge of the spherical obstacle is contained in the simulation region. The normal component of the velocity is removed if a particle collides with the obstacle. Since the complete obstacle is not contained in the simulation region, a steady state can not be achieved if no flow occurs through the obstacle. This is because the electric field would be zero at the back edge of the simulation region inside of the obstacle so that the incoming magnetic flux cannot be let out of the simulation region. Because only the front edge of the obstacle is retained in the calculation, magnetic flux cannot be eliminated by reconnection, as occurs in two dimensional MHD calculations when the entire obstacle is kept in the grid (Ogino et. al., 1986). It should be noted that two dimensional MHD simulations with an obstacle suffer from similar problems with regards to the magnetic flux.

In the present calculation, in order to let flow occur through the obstacle the coordinate perpendicular to the simulation plane is kept for the particles. Particles that collide with the obstacle can then flow through it after many collisions, provided the obstacle is treated as an object with a finite extent out of the simulation plane. A steady state then becomes possible and simulations show that indeed a steady state is achieved. The plasma density for such a steady state is shown in Fig. 1. Once a steady state is achieved, the shock is separated from the obstacle and so the obstacle does not impact the processes occurring at the shock front. Initial results suggest that high energy particles exiting the shock from the quasiparallel side of the shock originate from multiple reflections of incoming ions on the shock surface, as shown in Fig. 2.

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Figure Captions

Figure 1. Plasma density relative to the incoming value after steady shock is achieved. The Alfven Mach number is 10. The calculation is performed on a 700 by 160 grid and involves ≈ 2.5 million particle ions.

Figure 2. Generation of energetic particles at the shock front. Shown is the magnetic field lines (solid lines), the shock surface determined from the density jump (thick solid line), and test particle trajectories for (a) those test particles that had more than four times the initial ram energy at some time during their orbit and (b) those test particles that had more than nine times the ram energy at some point in their orbit.

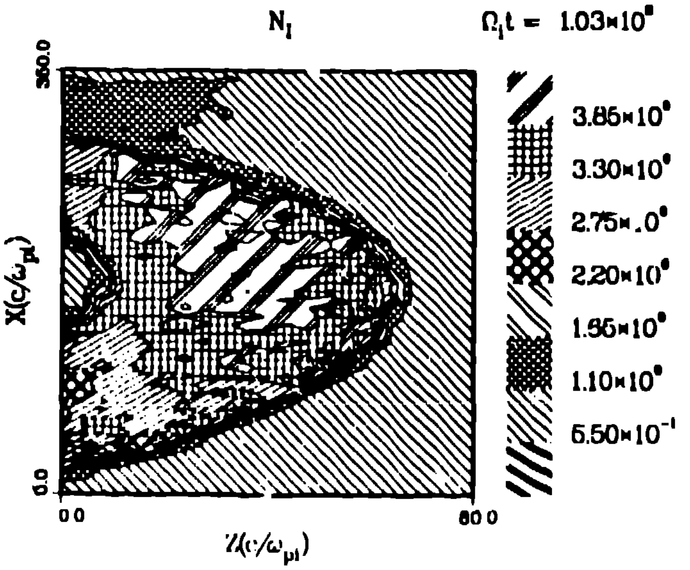

Figure 1.

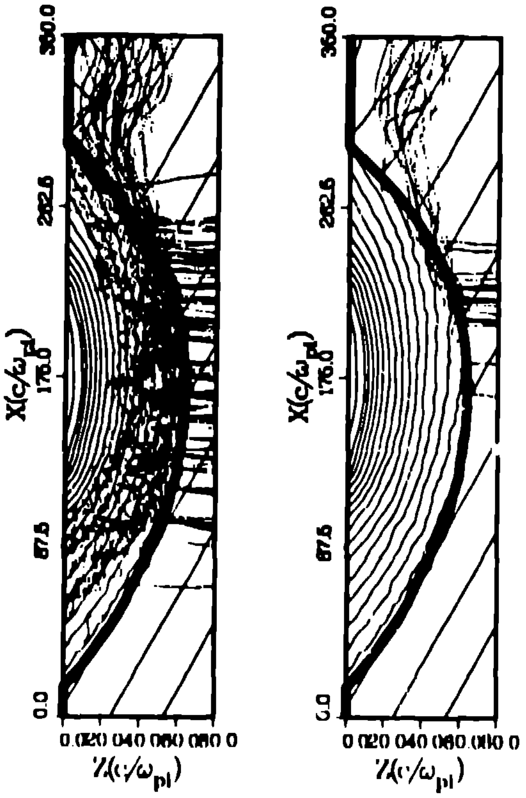

Figure 2.