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Full-particle 2-D Simulations of the curved terrestrial collisionless shock: turbulence and kinetic effects

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INTRODUCTION

The solar wind with a bulk velocity of 300-600 km/sec encounters the terrestrial magnetosphere which plays the role of a magnetic obstacle. Since its flow is in supersonic regime, a bow shock is formed ahead of the magnetopause (limit of the terrestrial magnetic field). This shock plays a crucial "shelter" role since it is the first terrestrial frontier met by the solar particles. It acts as an energy converter, transforming the bulk flow of the solar wind into local plasma acceleration and heating. This conversion takes place in association with nonstationary processes at the shock front. These processes have been evidenced both in numerical simulations and in local experimental satellite observations. Solar wind particles are decelerated through this shock and suffer local waves-particles interactions in such a way that a certain percentage of ions and electrons are reflected and injected back into the solar wind. The aim of this study is : what are the basic differences between the planar and curved shocks in terms of shock nonstationarity (turbulence) and particles kinetic effects ? A large number of experimental and numerical studies have been already dedicated to the physics of collisionless shocks (a recent review may be found in "Cluster results" [1]) . The main features of the shock pattern (precursor, ramp, overshoot, undershoot) and of particles dynamics (ion ring distributions, flat-top electrons distribution) for quasi-perpendicular shocks have been recovered in many previous theoretical/numerical studies. Nevertheless, several simplifying assumptions are involved :

- Shock waves often are assumed to be stationary. However, $1-D$ and $2-D$ simulations, have evidenced the non stationarity of the shock front [2]. Observations of the four satellites CLUSTER mission also confirm the nonstationary behavior of the shock [1].
- Most previous works have assumed a *planar* shock wave. In the real situation, the bow shock has a two dimensional curved pattern. This raise up several questions: how does the nonstationary behavior (shock reformation, front rippling, microinstabilities in the foot) persist with curvature ? Moreover, electron/ion foreshock located upstream of the shock front can be analyzed self-consistently only with full curved shock simulations. These arguments stress out the importance of shock curvature.

NUMERICAL RESULTS

Present simulations have been performed with a $2-1/2$ dimensional, fully electromagnetic relativistic particle codes using standard finite-size particle techniques [3]. Electrons and ions dynamics, and associated time/spatial scalelengths are fully included in a self-consistent way. Details have been given in [4].

In order to validate present results with respect to previous works, and to emphasize the differences between planar and curved shock, slices of the various fields components versus time have been analyzed at different angles θ_{Bn}. Results are illustrated in Fig. 1. The following main points can be emphasized:

Fields dynamics

- The well known features of a supercritical collisionless shock (Mach number $M_A \approx 2.3$) are recovered: foot-ramp-overshoot-undershoot patterns. Ion phase space confirms that the foot is well related to a noticeable number of reflected ions.

- As previously observed in $1-D$ and $2-D$ simulations of a planar shock front, the shock front suffers a self-reformation for angles θ_o around $90°$. Present numerical results stressed out that this self-reformation does not result from any $1-D$ or $2-D$ planar shocks artefact and persists within a certain angular range $(90°, 80°)$.

- Another source of turbulence is the front rippling which also persists but occurs within a smaller angular range of θ_o than as observed in $2-D$ planar shock. This rippling has an impact on both electrons and ions dynamics.

- The magnetic field continously evolved from a well defined step profile characterized by a narrow thickness for $\theta_{Bn} = 90°$, to a broader and more turbulent type profile lying over a wider space range in the upstream region as θ_{Bn} decreases from $77.5°$ to $65°$. Such a behavior was not observed in $2-D$ planar simulations even for large deviation shock ($\theta_{Bn} = 55°$ in [4]).

- Local Mach number M_A slighlty increases from $M_A \approx 2.3$ to ≈ 3, as θ_{Bn} decreases from $\theta_{Bn} = 90°$ to $71.25°$. For the case $\theta_{Bn} = 65°$, an estimate of the Mach number is difficult since the upstream turbulence does not allow to define precisely the location of the shock transition.

- The foot structure persists in front of the shock until a critical angle $\theta_{Bn} \leq 70°$. The foot is progressively hidden in the upstream turbulence and can only be observed in density

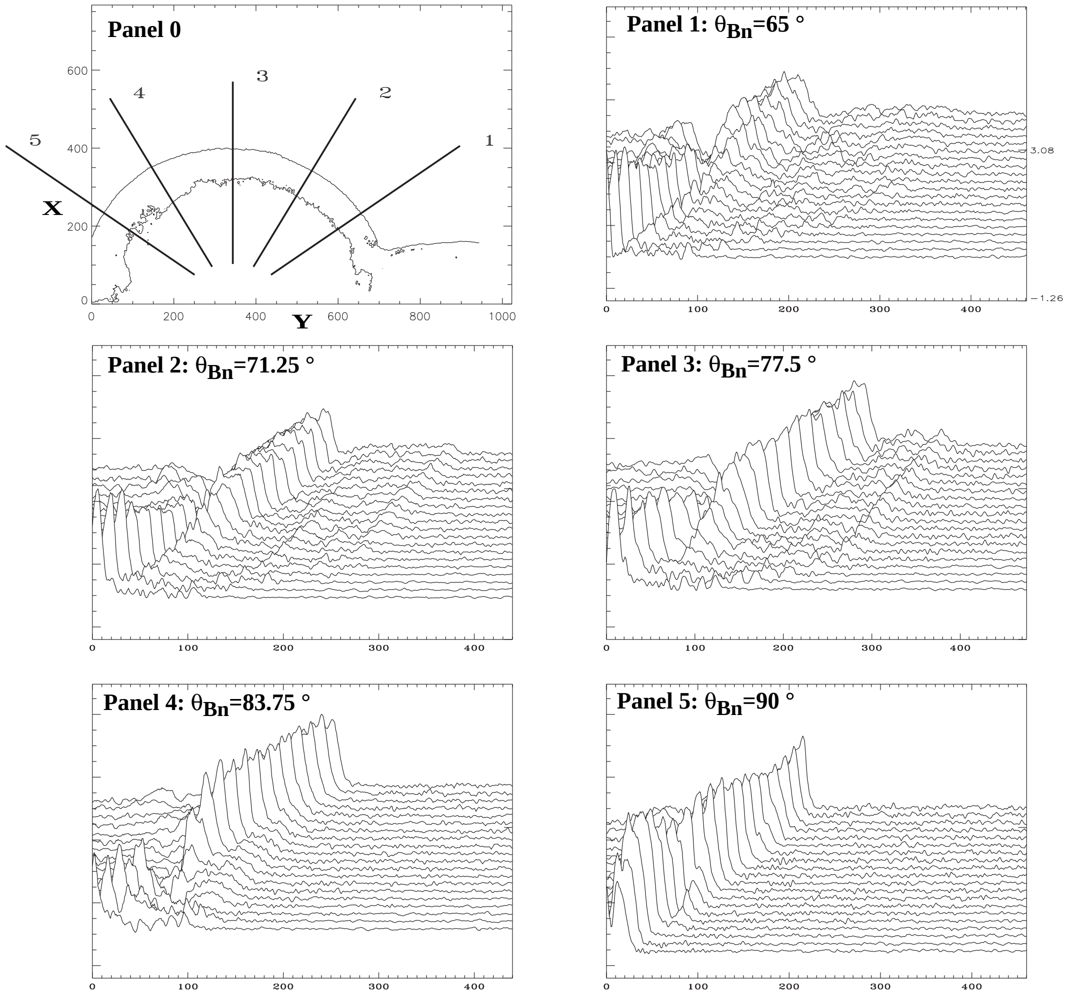

Figure 1: Behavior of the main magnetic field component versus time and at different angles. Each panel represents stackplots of $\widetilde{B}_{tz}$ at different times (with an interval time of $\Delta t = 24\widetilde{\omega}_{pe}^{-1}$ (or $3.84\widetilde{\omega_{pi}}^{-1}$)). For reference, the $X-Y$ simulation plane is plotted (panel 0) at a given time ($t = 1\tau_{ci}$) where the locations of the different slices are represented.

profile and not anymore in the field components profiles as in 1-D and 2-D planar shock. This can be explained in terms of ions reflection efficiency at the shock front by the electrostatic potential layer that would develop above the critical Mach number.

Ions dynamics

As in $2-D$ planar shock simulations [2], ion reflection becomes progressively less efficient as θ_{Bn} decreases, and a critical angle θ_c can be defined below which no ion reflection is observed. Characteristic loop of reflected ions at the shock front is well evidenced as θ_{Bn} decreases from 90° to 75°, but disappears as $\theta_{Bn} \leq 75^\circ$. One important point is that the number of reflected ions which pilled up in front of the shock is lower in $2-D$ curved shock than in $2-D$ planar case.

Geometrical effects must be invoked to account such differences.

Electron dynamics and electron foreshock

One important result is the evidence of the electron foreshock without any simplifying assumption. The foreshock region is commonly defined as the region of space extending between the curved shock front and the upstream magnetic field tangent to the shock. This region is characterized by the presence of energetic particles backstreaming upstream away from the front along the magnetic field lines connecterd to the curved shock.

SUMMARY AND CONCLUSIONS

The present study shows results of full particle simulation of a collisionless curved shock. In contrast with previous works, both electron and ion scales are fully and self-consistently involved. In short, the main expected characteristics of the field profiles and of the ion dynamics are fully recovered. For comparable Mach regime and quasiperpendicular propagation range, some differences between curved and planar shocks are: (i) fields exhibit some noticeable upstream turbulent pattern in upstream region for larger deviations from 90°; (ii) the density of reflected ions is lower because of some numerical artefact inherent to the planar shock models. One consequence is that the self-reformation of the shock front is restricted within a smaller angular range around 90° as compared with planar shock. (iii) A key result is the self-consistent evidence of the electron foreshock without any simplifying assumption (not accessible with planar shock).

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