Global Hybrid Simulations of the Bow Shock

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Abstract. This paper summarizes recent results from global hybrid (kinetic ions, fluid electrons) simulations of bow shocks or waves associated with solar wind interaction with magnetic dipoles of various strengths. By virtue of resolving ion temporal and spatial scales, global hybrid simulations account for collisionless dissipationary processes at and upstream of the shock and their effects on the macrostructure of the bow shock, ion foreshock and the magnetosheath. The results demonstrate that as the level of magnetization increases and the dipole becomes a more effective obstacle, the quasi-perpendicular part of the bow shock forms first and that formation of quasi-parallel part of the bow shock is led to the generation of oblique magnetosonic waves which steepen to form shocklets in the upstream region.

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INTRODUCTION

Over the past three decades, our knowledge of collisionless shocks in general and planetary bow shocks, in particular, has increased greatly (see e.g. review articles in [1,2]). Multiple spacecraft such as ISEE and AMPTE, coupled with local, electromagnetic hybrid (kinetic/PIC ions, fluid electrons) and full particle simulations have led to a much better understanding of the shock micro-structure and dissipationary processes under a variety of Mach numbers, shock normal angles and plasma beta (ratio of kinetic to magnetic pressure). In particular, the shock is divided into sub- and super-critical, as well as, quasi-parallel and perpendicular classes based on Mach number and shock normal angle respectively. Examination of the observed amount of heating in electrons and ions across the shock has established that ions are the dominant species in the dissipational processes and determination of the temporal and spatial scales of the shock. The only exception to this general conclusion could be the super-critical, perpendicular regime where electron dynamics and scales may be important (see e.g. article by Scholer in this book). The next important set of questions regarding the physics of the bow shock and its influences on the magnetosphere are related to the macrostructure of the shock under a variety of solar wind conditions. In recent years, we have used global (2-D in space, 3-D in fields and currents) hybrid simulations of solar wind interaction with magnetic dipoles of various strengths to gain a better understanding of the resulting bow shocks/waves, as well as, magnetospheres (e.g. [3,4,5,6,7]).

In this paper, due to lack of space, we only briefly summarize the results and conclusions of these studies and refer the interested readers to them for more details and comprehensive list of references.

RESULTS

The weakest type of interaction between the solar wind and a magnetic dipole corresponds to the generation of a whistler wake which does not affect the flow of the solar wind. As the dipole strength increases, fast and slow magnetosonic wakes are also generated which result in flow diversion and formation of a plasma tail. Formation of a bow shock/wave does not take place until the dipole strength is large enough for the plasma to become stagnant upstream of the dipole (i.e., formation of some form of magnetopause). We define the parameter $D_p$ as the distance (normalized to ion skin depth), upstream of the dipole, where dynamic pressure of solar wind and magnetic pressure are in balance. The appearance of a bow shock/wave occurs at $D_p \sim 1$. The left panel in Fig. 1 shows the density in the simulation box for $D_p = 2.1$, illustrating an example of such a bow shock/wave. The top and bottom panels on the right hand side of the figure show variations of plasma and field values across the upper and lower portions of the bow shock/wave respectively.
In this run, the interplanetary magnetic field (IMF) makes a 45° angle with the X-axis and thus the upper (lower) portion of the bow shock corresponds to quasi-perpendicular (parallel) geometry. The top right-hand panel in Fig. 1, shows changes in plasma and fields consistent with those associated with quasi-perpendicular, fast magnetosonic shocks. On the other hand, the changes seen in the lower panel are not consistent with a shock crossing and have been interpreted as a combination of a fast magnetosonic wave followed by a rotational discontinuity. The former results in flow diversion while the latter accommodates the change in the direction of magnetic field from the solar wind to the draped fields in the tail. Thus, the quasi-perpendicular part of the bow shock has formed while the quasi-parallel has not and overall constitutes a bow shock wave. Even though the quasi-parallel section of the bow shock has not formed, ion reflection near the nose of the bow shock and leakage from the quasi-parallel magnetosheath lead to a population of backstreaming ions whose interaction with the solar wind results in generation of ULF waves. This ion foreshock region is illustrated in Fig. 2 which shows ion temperature and magnetic field lines in the simulation box. The insert shows the profile of parallel propagating, non-convective, sinusoidal, ULF waves generated in the foreshock region. These waves are generated through the right-hand resonant ion-beam instability [8] and result in scattering of the field aligned beam into a broader distribution in pitch angle without affecting the solar wind in any significant way. They possess all the properties of 30 second, sinusoidal, ULF waves observed in the earth's foreshock [9].
It was shown by [4] that when $D_p \approx 20$, the resulting magnetosphere has a terrestrial structure and the bow shock is well developed. Figure 3 shows the results of simulations for $D_p = 64$, which corresponds to Mercury's level of magnetization, in a format similar to that in Fig. 1. The IMF in the run has the same orientation as the $D_p = 2.1$ case, and the upper (lower) portion of the bow shock corresponds to quasi-perpendicular (parallel) geometries. The right hand panels show 2 crossings of the quasi-parallel shock with one (top) closer to the nose and the other (bottom) further in the flank. As can be seen, in both cases the transition from solar wind to the magnetosphere takes place in a number of steps which is the result of local heating and deceleration of the solar wind by the upstream generated waves. The shock profile is highly turbulent and time varying due to convection of the upstream generated ULF waves into the shock and its cyclic reformation [e.g. (10)]. Examination of the ULF waves generated in this run and the ion distribution functions in the foreshock by [5,7] has revealed the presence of both parallel and obliquely propagating waves with the former being generated by field aligned ion beams and the latter by gyrating ions closer to the quasi-parallel shock. The right hand panels in Fig. 4 show examples of both waves, with the oblique ones (top) having steepened to form shocklets (e.g. [9]) and the parallel ones (bottom) having a sinusoidal wave form as in the $D_p = 2.1$ case.

That these two types of waves are generated through different instabilities is consistent with the suggestion by [11] who used linear theory and local, 2-D hybrid simulations and observations of ion beams in the foreshock [12]. The results also demonstrate that generation of shocklets is essential for the formation of the quasi-parallel shocks.
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REFERENCES