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Reflection of Solar Wind protons on the Martian Bow shock: Investigation by means of 3-dimensional simulations

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Abstract

Having run a self-consistent three-dimensional simulation of the Martian bow shock we subsequently investigate the reflection of solar wind protons on the planetary bow shock by means of test particles moving in the stationnary electromagnetic field generated during the self-consistent simulation. This two-step approach allows to identify reflected particles without impeding the main stream of computation during the self-consistent run.

1. Introduction: Particles reflected by planetary bow shocks

1.1. *In situ* observations

Since the first unambigous identification by Asbridge et al. [1] of solar wind ions reflected and accelerated by the Terrestrial bow shock numerous case and statistical studies have been conducted on different planetary shocks. The Terrestrial shock is the best documented one, see for example the recent review by Eastwood et al. [5]. The first observation of reflected ions, both native and newborn, at the Martian bow shock has been presented by Dubinin et al. [3].

1.2. Investigations by means of numerical simulations

Simulation studies of ion reflection at collisionless shocks started with Burgess [2] using a one-dimensional hybrid code. Numerous simulations followed but only very few addressed processes at curved bow shocks and to our knowledge none was three-dimensional. Thomas and Winske [7] conclude from their two-dimensional study, made possible by an astute trick to avoid the piling up of the magnetic flux in front of the planetary obstacle, that "the vast majority of foreshock ions originate on the quasi-parallel side of the shock". We present here the first genuinely 3-dimensional simulation study of the Martian ion foreshock.

2. Self-consistent hybrid and test particle simulations

The 3-dimensional hybrid simulation model of Modolo et al. [6] has been run with parameters given in Table 1 to simulate the interaction of the solar wind with Mars. The stationnarity of the computed solution can be ascertained by checking the stationnarity of local fields and moments of the velocity distribution functions of the various species. Test particles, only solar wind protons, are injected into the simulation domain from the entry face of the solar wind and followed till they exit the simulation domain or penetrate into the Martian atmosphere. Reflected particles are identified as accelerated particles returning to the free solar wind after a single or multiple encounter with the bow shock.

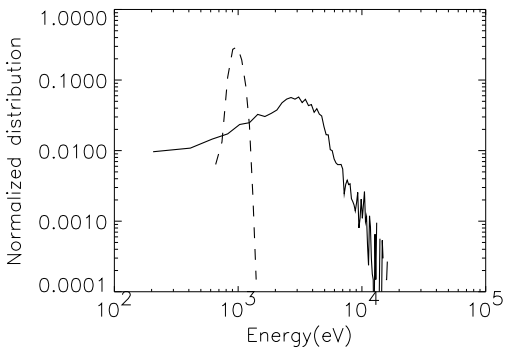

Figure 1: Energie spectrum of solar wind protons after reflection on the Martian bow shock (continuous curve) compared to their initial spectrum.

NB The stationnary electromagnetic field generated by the hybrid simulation contains spatial fluctuations

Table 1: Solar Wind parameters of the self-consistent 3d hybrid simulation

parameter	value	unit
IMF X comp.	1.32	nT
IMF Y comp.	0.0	nT
IMF Z comp.	2.12	nT
H^+ density	1.25	cm^{-3}
$He^+ +$ density	0.05	cm^{-3}
electron density	1.3	cm^{-3}
H^+ temp.	9	eV
electron temp.	14	eV
Alfven velocity V_A	44.4	km s^{-1}
bulk velocity	11.5	V_A
	500	km s^{-1}
$c\omega_{p,H}^{-1}$ H^+ inertial length	203	km
$\omega_{c,H}$ H^+ cyclotron puls.	0.24	rad s^{-1}
time step	0.1	$\omega_{c,H}^{-1}$
spatial step	1.5	$c\omega_{p,i}^{-1}$

but time fluctuations are frozen, this limitation should be reminded and its consequences evaluated by comparison with self-consistent simulations.

3. Summary and Conclusions

The adopted two-step approach allows a detailed analysis of the reflection of solar wind protons on the Martian bow shock. Reflected solar wind protons originate from a cylinder of the incoming bulk flow having a rather limited transversal extent, and most of them exit the acceleration region in the parallel shock. The energy spectrum of the reflected protons extends from a few 10^2eV to 10^4eV. A similar study will soon be made for pickup ions generated upstream of the bow shock in order to extend the analysis of Dubinin et al. [4].

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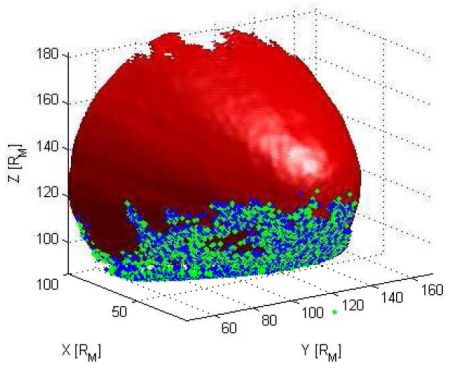

Figure 2: Simulated 3d Martian bow shock with overlaid entry (blue) and exit (green) points of the reflected solar wind protons: in case of multiple encounters of a given test particle with the shock, entry means the first entry and exit the last exit. These overlaid points cover part of the perpendicular shock and all the visible part of the parallel shock region at the bottom part of the red surface.

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