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Mars in the Solar Wind - Simulations and Observations

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Abstract

The physics of the interaction of unmagnetized planets with the Solar wind has been investigated since the first Mariner spacecraft did reach Mars and Venus more than 50 years ago. Magneto hydro-dynamic models were able to predict the formation and location of the bowshock in front of these planets. More sophisticated models of the interaction with the magnetized solar wind later could demonstrate the global static picture of the plasma environment of Mars and Venus. But earlier models were rarely able to model dynamic effects and the timing of physical process in this interaction. We here use the open source PLUTO code in its 3D spherical hydrodynamic and magneto-hydrodynamic version. We also develop a multi-species extension of this code. We investigate the interaction of the solar wind with the ionosphere of Mars with the aim to understand the importance of different physical effects on bow shock location, ion escape and current structures. We compare these simulations to recent observations by the MAVEN spacecraft.

1. The Simulation

We use the open source simulation code PLUTO [1] [1]. The basic implementation of the conservation laws follows [2] similar as for the well known BATS-R-US code for Mars [3]. The simulations shown here use both the hydrodynamic (HD) module of the code and the magneto-hydrodynamic (MHD) module in spherical coordinates. Here we do not use the adaptive grid module of the code which is only optimized for cartesian coordinates. Since our aim is to find out which minimum set of physics is sufficient to describe the major large scale observations we do neither include gravitational forces, nor ionization of a neutral background, nor cooling, nor other minor physical effects. We use an ideal equation of state ($\gamma = 5/3$), selective entropy and flattening for shock catching, parabolic reconstruction, Runge-Kutta time stepping and the Rieman solver HLL. In the MHD module we use the eight-waves formulation for div B control. The simulation box size is 256x128x256 in r, θ, ϕ covering radial distances r between the ionospheric peak at 140km altitude to 2 Martian radii (6780km) in logarithmic spacing. This corresponds to a resolution of about 15km in the ionosphere and 60km at largest distance. The solar wind mass density and velocity are assumed constant at 1 amu/cm^3 and 400 km/s. We also assume a constant viscosity typical for the solar wind. The ionosphere is modeled by a Chapman profile with peak altitude at 140km and a scale height of 30km. Peak mass density at dayside noon is 10^6 amu/cm^3 and 10^4 amu/cm^3 on the night side. This peak density at the inner boundary is kept constant throughout the run. All other boundaries are kept at an outflow boundary condition (zero gradient). In the MHD runs we use a constant interplanetary magnetic field (IMF) of Bx=By=3nT. Simulationas are done using parallel message passing interface (MPI). Typical computation times are 6min per 1s real time on a 48 processor 2.8GHz computer.

If we launch the simulation with a constant solar wind running initially against a resting ionosphere we observe that a bow shock forms within 1s real time and reaches its nominal and constant stand-off distance at noon after about 30s real time in MHD and about 100s in HD. The bowshock distance and shape are almost identical in the pure hydrodynamic and MHD model. This means that the sound speed is largely dominating the formation of the shock position and magnetic effects play a minor role. Only in the MHD model an assymetry forms in that the bowshock forms further inward on the quasi-parallel side and further outward on the quasi-perpendicular side (see Fig.1). A steady state magnetosheath forms after about 200s real time

[1] http://plutocode.ph.unito.it/

at least within the spherical domain simulated here. Fig.1 shows a cut through the simulation box in the XY plane, where X points away from the solar direction and the plane contains the IMF vector. Shown are the magnetic field magnitude in color and direction as yellow arrows. The thin yellow and orange lines indicate the mean bowshock and pile-up boundary position observed by the MGS spacecraft [4].

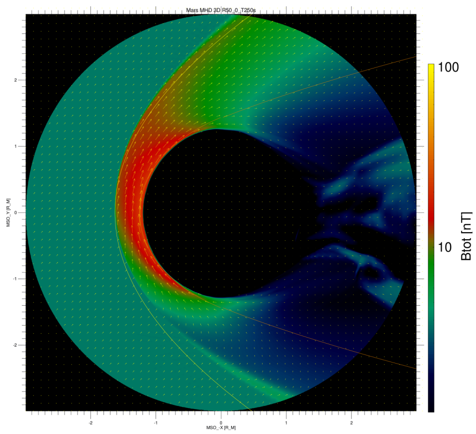

Figure 1: 3D MHD simulation of the IMF draping around Mars. Shown is the field magnitude and the field vector in the IMF plane after 250s real time. Thin lines show the mean observed bowshock and MPB location[4].

2. MAVEN Observations

As an example for the comparison with observations we show in Fig.2 the median values of magnetic field magnitude (color) and direction (arrows) observed by the MAVEN spacecraft in 2015 in the XY plane of Mars Solar Electrical frame, where X points toward the Sun and the XY plane contains the mean upstream IMF field vector observed on each orbit.We observe that the magnetic field draping pattern in the magnetosheath agrees well with the simulation. The higher field magnitude observed in the ionosphere is due to crustal magnetization. We also observe that our simple MHD model does show a much lower magnetization of the tail inside of the MPB.

3. Conclusions

The PLUTO code provides an excellent open source simulation base to investigate fundamental problems

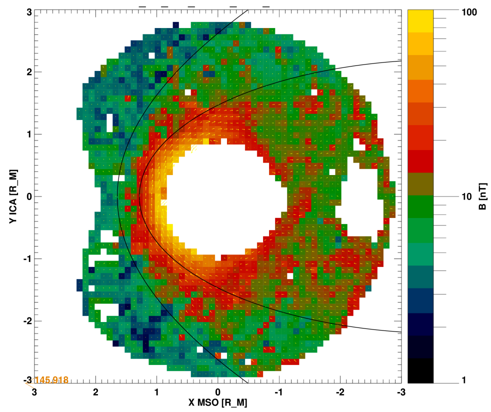

Figure 2: Median values of magnetic field magnitude (color) and direction (arrows) observed by the MAVEN spacecraft in 2015 in the XY plane of Mars Solar Electrical frame. Thin lines show the mean observed bowshock and MPB location[4].

in planetary plasma physics. Together with the growing database of plasma observations at Mars provided by the MarsExpress and MAVEN spacecraft it promises to significantly improve our understanding of the interaction of stars with planets.

Acknowledgements

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