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Mars as a comet: Solar wind interaction on a large scale

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ABSTRACT

Looking at the Mars–solar wind interaction on a larger spatial scale than the near Mars region, the planet can be seen as an ion source interacting with the solar wind, in many ways like a comet, but with a smaller ion source region. Here we study the interaction between Mars and the solar wind using a hybrid model (particle ions and fluid electrons). We find that the solar wind is disturbed by Mars out to 100 Mars radii downstream of the planet, and beyond. On this large scale it is clear that the escaping ions can be classified into two different populations. A polar plume of ions picked-up by the solar wind, and a more fluid outflow of ions behind the planet. The outflow increases linearly with the production up to levels of observed outflow rates, then the escape levels off for higher production rates.

1. Introduction

The interaction between the solar wind and Mars provides one way that the atmosphere of Mars can be lost. As soon as neutrals in Mars atmosphere are ionized, e.g., by photoionization, they are subject to electro-magnetic forces and can be accelerated and subsequently escape the planet. To quantify the present loss of atmosphere at Mars, it is therefore of interest to understand how ions can escape the planet under different conditions. In the past, ion outflow has been observed by the Phobos-2 (Lundin et al., 1989) and the Mars Express (Lundin et al., 2004) missions. In the most general sense, the loss of ions from Mars can be seen as a mass loading (Szegö et al., 2000) of the solar wind, similar in some ways to the mass loading at comets, but with a smaller ion source region. If we go to even larger spatial scales, the fluxes of ions produced near Mars will be too tenuous to affect the solar wind, and behave like an expanding cloud of ions. Here we focus on the intermediate region, far away from the planet, but not so far away that the solar wind is unperturbed. What is the morphology of the ion outflow, and the global interaction of the planet with the solar wind? What is the morphology of the bow shock in the far wake region? The tool we use is a hybrid model (particle ions and fluid electrons) of the interaction between Mars and the solar wind, that we describe in the next section.

The solar wind interaction with Mars has been modeled by many groups using different kinds of models, e.g., empirical (Kallio and Luhmann, 1997) test particles (Fang et al., 2008), magnetohydrodynamic (MHD) (Ma et al., 2004), multi-fluid (Harnett and Winglee, 2006) and hybrid models (Brecht, 1990; Kallio and Janhunen, 2001; Modolo et al., 2005; Bößwetter et al., 2007).

The advantage of fluid models is that they are computationally less expensive than hybrid models, allowing finer grid resolution. On the other hand, hybrid models contain a more accurate description of the ion physics, something important at Mars where the planet is of similar size as the ion length scales, such as the ion gyro radius and the ion inertial length. We can note that a comparison of many different models of the interaction of Mars with the solar wind found significant differences in the general interaction for the different models (Brain et al., 2010).

One thing in common to past model investigations is that they have consider the near Mars region, up to a few planet radii away from the planet. This is natural since the aim of the studies has been focused on topics such as determining the loss of heavy ions to space. This requires that the model resolves the ionospheric region well with high spatial resolution. This implies a high computational cost for a large simulation domain, so the domain is chosen just large enough for the process under study. For ion escape studies the simulation domain just has to be large enough that there is no significant returning heavy ion flux.

Previous studies has found that the escaping ions can be classified into two different populations. A polar plume of ions picked-up by the solar wind, and a more fluid outflow of ions behind the planet. In hybrid simulations Brecht and Ledvina (2012) found tailward electric fields in the hemisphere opposite to the solar wind convective electric field the accelerate heavy ions such that they escape downstream behind the planet. The ion plume has been described based on Mars Express observations (Liemohn et al., 2014) and has also been studied using test particle simulations (Curry et al., 2013).

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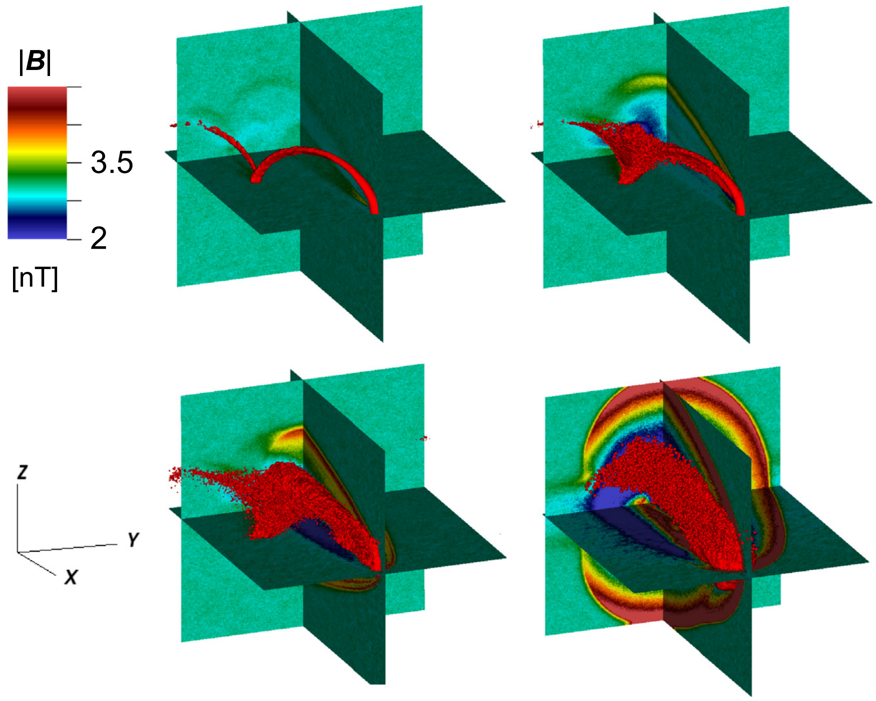

Fig. 1. Results for relative heavy ion production of 0.01 (top left), 0.1 (top right), 1 (bottom left), and 10 (bottom right). Iso surface of heavy ion number density of 0.01 cm^{-3} is shown in red. The colors of the cuts show magnetic field strength according to the color bar. The simulation domain extends to $50R_M$ down stream of Mars, and the solution is at $t=1200$ s. The cut perpendicular to the x-axis is at $x=-1.6\cdot10^8$ m. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

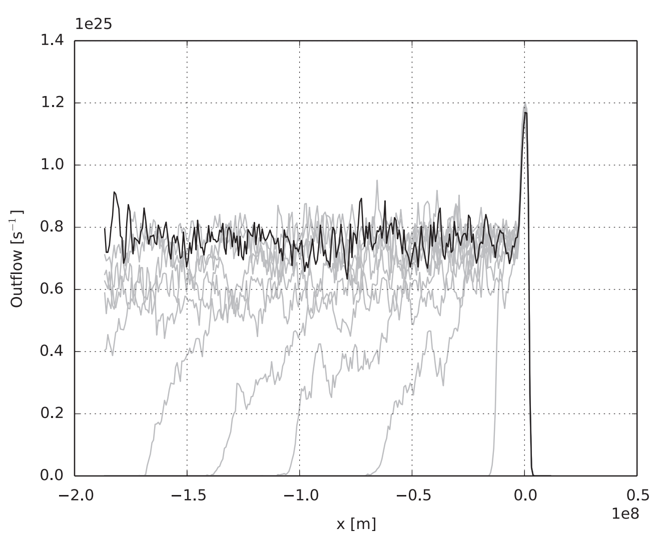

Fig. 2. Total O^+ number flux through planes perpendicular to the x-axis for a relative heavy ion production of 1, at different times. The black line is at the final time of 1100 s, and the grey lines are at earlier times in intervals of 100 s.

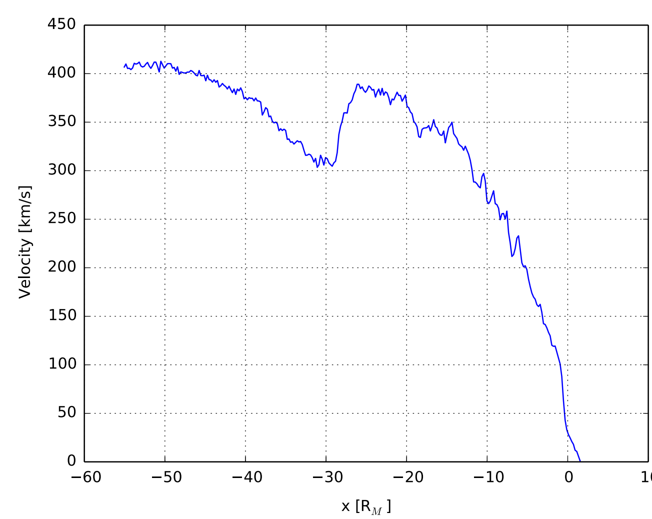

Fig. 3. The average velocity of O^+ ions in planes perpendicular to the x-axis for a relative heavy ion production of 1, after 1100 s. The velocity is computed as the total ion current divided by total charge in each plane.

Table 1
Total outflow of O^+ ions as a function of normalized production.

Production	0.01	0.1	1
Outflow [s^{-1}]	$2.8\cdot10^{23}$	$2.6\cdot10^{24}$	$0.7\cdot10^{25}$

2. Model

In what follows we describe the details of the computer model we use to study the large scale plasma interaction between Mars and the solar wind. The model has previously been applied to the solar wind interactions of the Moon (Holmström et al., 2012) and the plasma interactions of Callisto (Lindkvist et al., 2015). First we describe the plasma model, then the heavy ion production, and finally the boundary conditions.

2.1. Hybrid model

In the hybrid approximation, ions are treated as particles, and electrons as a massless fluid. In what follows we use SI units. The