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Dynamics of planetary ions in the induced magnetospheres of Venus and Mars

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ABSTRACT

We compare dynamics of planetary ions in the induced magnetospheres of Venus and Mars in a global hybrid simulation to study factors controlling the ion escape at unmagnetized planets. In the simulation we find that the finite Larmor radius (FLR) effects of escaping heavy ions are stronger at Mars than Venus under nominal solar wind conditions. But, varying upstream conditions, especially the IMF, affects the strength of the FLR effects. We classify three basic types of planetary ion dynamics in an induced magnetosphere. First, light ions such as hydrogen follow the E × B drift, and escape in the wake in the hemisphere where the solar wind convection electric field is pointing towards the planet. Second, heavy ions like oxygen undergo FLR effects, and escape mainly outside of the wake in the hemisphere where the solar wind convection electric field is pointing away from the planet. Third, ion species between light and heavy ions can have both the E × B and FLR type dynamics in the same time.

1. Introduction

Venus and Mars do not have global intrinsic magnetic fields and they lose ions from their ionospheres and exospheres due to the interaction with the solar wind (Luhmann et al., 2006; Barabash et al. 2007a,b; Fedorov et al., 2011). The ion escape erodes not only lighter ion species but also heavy ions like oxygen, which are otherwise gravitationally bound to the atmospheres of terrestrial planets. Both Venus and Mars are similar in that they have an atmosphere composed mainly of carbon dioxide and they have likely lost most of their original water to space. On the other hand, Mars is smaller and farther away from the Sun than Venus. The significance of the solar wind induced removal of heavy elements from Venus and Mars during the evolution of the solar system is debated (Luhmann and Bauer, 1992; Lammer et al., 2008).

An induced magnetosphere is formed via the piling up of the interplanetary magnetic field (IMF) when the solar wind interacts with an unmagnetized planet (Bertucci et al., 2011). The obstacle to the magnetized solar wind flow is the highly conducting ionosphere. The relative size of the induced magnetosphere and plasma environment of Venus and Mars are about the same if measured in planet radii (see Figure 1 in Fedorov et al., 2008). But, the radius of Mars ($R_M = 3390$ km) is about half the radius of Venus ($R_V = 6051.8$ km) and, thus, the "radius" of the Mars induced magnetosphere is also about half of the "radius" of the Venus induced magnetosphere when measured in absolute length units. A typical O^+ pickup ion in the upstream solar wind has the Larmor radius of 4000 km at Venus and 13,000 km at Mars (Jarvinen and Kallio, 2014), whereas typical H^+ inertial length and pickup H^+ Larmor radius are smaller than the radii of Venus and Mars (Ledvina et al., 2008).

Planetary ions are energized by several processes in an induced magnetosphere. A basic form of ion energization at Venus and Mars is cometary type ion pickup, which occurs when a planetary particle is ionized in the upstream solar wind or in the magnetosheath and is accelerated by the solar wind convection electric field (Coates, 2004). Further, electric fields related to, for example, draped magnetic fields and plasma waves in the plasma environment of an unmagnetized planet lead to acceleration of planetary ions. Ion escape regions and ion acceleration processes at unmagnetized planets have been studied in numerous works. A recent review can be found in Dubinin et al. (2011).

The semimajor axis of the orbital motion around the Sun is 1.524 AU for Mars and 0.723 AU for Venus. This means that Venus and Mars experience different average solar wind and IMF conditions. The biggest differences in the average upstream conditions are the solar wind density, the IMF magnitude and the IMF spiral or cone angle (the angle between the IMF and solar wind velocity vector). Typical upstream solar wind and IMF conditions and their

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scalings at terrestrial planets are listed in Tables 1 and 2 of Slavin and Holzer (1981).

In the approximation of scatter-free single particle motion it is straightforward to derive how the behavior of planetary pickup ions in the undisturbed solar wind is related to the upstream conditions. Pickup ions undergo the E × B drift and gyro motion with Larmor radius of (Jarvinen and Kallio, 2014)

$$r_L = \frac{mV_{E\times B}}{qB} = \frac{m}{q}U_{sw}\frac{B_y}{B^2}, \tag{1}$$

where m/q is the mass-to-charge ratio of the particle, B is the IMF magnitude, B_y is the IMF perpendicular component to the solar wind velocity, U_{sw} is the solar wind speed and $V_{E\times B}$ is the E × B drift speed defined as $V_{E\times B} = U_{sw}\sqrt{B_y^2/(B_x^2+B_y^2)} = U_{sw}B_y/B$ (see Section 2.4 for definition of the coordinate system).

When the Larmor radius of a charged particle is comparable to the length scales of the studied phenomenon or the gyro motion is in some other way important for the ion dynamics, we refer to this as the finite Larmor radius (FLR) or kinetic effect.

The solar wind interactions and ion escape from Venus and Mars have been studied in several self-consistent hybrid and MHD simulation works (see reviews by Ledvina et al., 2008; Ma et al., 2008, and references therein). Further, several global models for the Mars-solar wind interaction participated in the SWIM Mars modelling challenge where ion escape was analyzed (Brain et al., 2010a).

Test particles have been used to study planetary ion escape at Venus and Mars in many works (Luhmann, 1990; Lichtenegger et al., 1995; Kallio and Koskinen, 1999; Luhmann et al., 2006; Fang et al., 2008; Curry et al., 2013). Test particles allow the analysis of trajectories of different ion species in given electric and magnetic fields. The mass-to-charge ratio of the traced species defines how test particles “see” the electric and magnetic field in an induced magnetosphere. Heavier species have larger Larmor radius (Eq. (1)) and they are expected to display stronger FLR effects than lighter species. Test particle tracings have been also used to estimate if the FLR effects of escaping pickup ions can affect the structure of the Venus induced magnetosphere (Phillips et al., 1987).

There have not been many published works comparing the Venus and Mars plasma environments even though the comparisons between the two planets are potentially useful in quantifying which factors control the solar wind induced ion escape from unmagnetized planets. In an early hybrid simulation study Brecht and Ferrante (1991) compared the interaction between different sized unmagnetized obstacles (corresponding to Venus and Mars) and the solar wind. Fedorov et al. (2008) compared the Mars Express ASPERA-3 and Venus Express ASPERA-4 observations of the solar wind and heavy ions around Venus and Mars side-by-side.

In this work we compare the dynamics of escaping ions in the plasma environments of Venus and Mars. We use a global hybrid simulation to model the interaction between the solar wind and Venus and Mars under different upstream condition cases. Further, we analyze the dependence of the planetary ion motion on the mass-to-charge ratio of the escaping species by tracing test particles in electric and magnetic fields from the hybrid model.

The study is organized as follows. The model and the simulation runs are described in Section 2. The results of the simulation runs are presented in Section 3. Section 4 discusses and synthesizes the simulation results. At the end in Section 5 we summarize our findings.

2. Model description

The numerical model used in this study is the hybrid simulation platform named HYB developed at the Finnish Meteorological Institute. The HYB model has been used to study plasma interactions of several solar system objects (e.g. Kallio et al., 2010; Jarvinen et al., 2010, and references therein). Here the model is used to compare the dynamics of escaping planetary ions in the plasma environments of Venus and Mars. Next we summarize the most important details of the model and describe the simulation runs analyzed in this study.

2.1. Hybrid model

In the hybrid model positively charged ions are treated as particles moving under the Lorentz force and electrons are a charge-neutralizing fluid. The electric field ($\vec{E}$) is defined by the electron momentum equation assuming massless electrons:

$$\vec{E} = -\vec{U}_e \times \vec{B} + \frac{\nabla p_e}{q_e n_e} \tag{2}$$

and the magnetic field ($\vec{B}$) is propagated by Faraday's law:

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}. \tag{3}$$

$\vec{U}_e$ is the electron velocity, which is derived from the total current density using Amperè's law and from the ion current density $\vec{J}_i$ as

$$\vec{U}_e = \frac{1}{q_e n_e}(\mu_0^{-1}\nabla \times \vec{B} - \vec{J}_i). \tag{4}$$

p_e is the electron pressure assuming isothermal electrons (T_e= const.) and ideal gas law as the electron equation of state ($p_e = n_e k T_e$) in the runs analyzed here. $q_e n_e$ is the electron charge density, which is assumed to provide plasma quasi-neutrality. That is, the sum of the electron and ion charge densities equals to zero in each grid cell. In Faraday's law finite resistivity outside of the inner boundary (the super conducting obstacle) is used to add diffusion in the magnetic field propagation.

In the hybrid approach the ion dynamics are self-consistently coupled with the electric and magnetic field via the ion current density and the ion charge density. Further, the ion velocity distributions evolve freely in the hybrid model whereas in fluid simulations a velocity distribution needs to be prescribed. See Jarvinen et al. (2009) for a summary of the equations of the HYB model and Kallio and Janhunen (2003) for details of the numerical solution of the equations.

2.2. Boundaries and ion production

In this work the inner boundary of the model is a super conducting shell, which the magnetic field cannot penetrate and, thus, it is the obstacle to the magnetized solar wind flow. The inner boundary is located approximately at the altitude of the exobase. In the HYB model a prescribed resistivity profile can be used to add diffusion of the magnetic field (e.g. Janhunen and Kallio, 2004).

Particle boundary conditions are defined at the inner and outer boundaries of the simulation domain. In this work absorbing particle boundaries are used for the inner and outer boundaries.

Planetary ions are injected in the simulation by two different types of sources in the simulation runs analyzed in this work. The ionospheric ions are emitted from a spherical shell near the inner boundary. The emission rate per unit surface area has a cos(SZA) dependence at the dayside, where SZA is the solar-zenith angle, and is constant at the nightside. The exospheric photoions are produced by photoionization of planetary neutral coronae. Venus runs include the ionospheric H^+ and O^+ emission and the exospheric H^+ and O^+ photoion production. Mars runs include the ionospheric O^+ and $O_2{}^+$ emission and the exospheric H^+ and O^+ photoion production. The Venus neutral corona profiles are the

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