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Simulations of stellar winds and planetary bodies: Ionosphere-rich obstacles in a super-Alfvénic flow

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ABSTRACT

We classify the interactions of planetary obstacles with an upstream stellar wind. The investigation of each type of interaction is made using a three dimensional simulation code based on the hybrid modeling of the interplanetary plasma (the AIKEF code). The aim is to fill up the parameter space of magnetospheric interactions. In this work, we focus on highly resistive obstacles, non-magnetized but possessing an ionosphere. We examine different ionospheric types by focusing on one parameter: the ionospheric production. Two types of ionospheric ions are used: H^+ and O^+, to show the influence of ionospheric ion mass on the interaction region configuration. The interaction types are classified using an equivalent conductivity of the ionosphere. The resulting induced magnetospheric interactions are described using the currents flowing throughout the interaction region. The essence of the interaction region structure is summarized into three-dimensional diagrams of the current distribution. The results show three main stages of development. The first is a lunar-type interaction with raising asymmetries. The second is depicted by the presence of a growing induced magnetopause and an interaction region which asymmetry depends on the mass of the ionospheric ions. The last stage is a fully developed induced magnetosphere, or Venus-like interaction, with a symmetric magnetosphere.

1. Introduction

Unmagnetized obstacles in the Solar System interact with the Solar wind in different manners. Inert and ionosphere-less obstacles (e.g., the Earth moon) generate a wake on the nightside of the interaction region (Whang, 1968). Ionosphere-rich obstacles (e.g., Venus) drag the solar wind and may trigger an induced magnetosphere balancing the solar wind pressure (Bauer et al., 1977; and references therein]. Studies of the solar wind - or any magnetized plasma - directly impinging an ionospheric-rich obstacle were done with Venus, Mars, comets, and several outer moons as Titan and Dione. In such a type of interaction, an induced magnetic field is generated by the encounter of the interplanetary magnetic field (IMF) and the ionosphere, which acts as a super-conducting shell encompassing the planet (Baumjohann et al., 2010). The term induced magnetic field here does not refer to a temporal variation of the IMF (see e.g. Jia et al. (2015)), it refers to a steady state field resulting from various processes. Various ionospheric mechanisms can generate the conditions necessary to trigger an induced field. The pick-up process (e.g. Phillips et al., 1987) consists of a transfer of momentum between the ionosphere and the impinging Solar Wind. It is also named “mass loading” and is the main effect discussed in this study. Collisions play a major role in solar wind interactions physics when the solar wind pressure is high enough to push the ionosphere down to the lower atmosphere. The net effect of collisions is expressed in the so-called Pedersen conductivity tensor (Baumjohann and Treumann, 1996).

Although numerous simulations of the interaction of an inflowing solar wind with planetary ions were performed with dense ionospheres (Venus-type or Mars-type), or weak sputtering and reflected particles (Wurz et al., 2007; Lipatov et al., 2012; Davis et al., 2014; Fatemi et al., 2014), fewer models were performed with different ionization rates. Such models investigating the effect of the production rate are typical for comets which, by approaching or moving away from the sun, are subjected to an extremely variable ion production rate (Cravens et al.,

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1987; Biver et al., 1997, Bagdonat and Motschmann, 2002a; Motschmann and Kührt, 2006). Variations of ionization rates at planetary obstacles may have many causes, either the evolution of the solar system (Kulikov et al., 2007), seasonal effects (Yamauchi et al., 2015), solar cycles (Russell et al., 2006), or complex mechanisms requiring dedicated modeling (Marchaudon and Blelly, 2015). The quantification of the picked up ions is a long-term study implying both modelings and measurements, aiming to a complete description of the involved mechanisms (Curry et al., 2015). General implications of the production rate in ionospheric interactions for non-solar system production rate requires extrapolation but are consistent, owing to the sturdiness of the simulation codes (Johansson et al., 2009; Jarvinen et al., 2009).

Currents in planetary interactions with an impinging magnetized plasma are helpful to provide a self-consistent description of the interaction region. Using the property that currents must close at steady state, exchange between the different regions of the whole interaction becomes easy to illustrate (Mauk and Zanetti, 1987; Siscoe et al., 2000, Siscoe and Siebert, 2006). Complete description of the current systems of unmagnetized airless body are available in the literature (Fatemi et al., 2013; Vernisse et al., 2013; Zhang et al., 2014; Simon, 2015). Currents systems of induced magnetospheres have also been detailed in the literature (Baumjohann et al., 2010). Currents and magnetic field distortions associated with picked up ion are particularly difficult to investigate when multiple species are present in the ionosphere, and simulating one species at a time may help resolve part of that challenge (Jarvinen et al., 2016).

A full coverage of types of interaction between airless unmagnetized bodies and unmagnetized bodies possessing a developed ionosphere remains to do. In this paper, we propose a simple description of the currents in the interaction region of an unmagnetized obstacle with an upstream solar wind, using various production rates. We perform a number of hybrid simulation runs (the AIKEF code, see Mueller et al. (2011)) using H^+ and O^+ ions for generating the ionosphere, based on a Chapman model. We vary the ionospheric ion production from zero to Venus-like production rate between the simulations and summarize the results in three-dimensional diagram using the major currents flowing in the interaction region. The main driver of the interaction is the mass loading, associated with the pick-up current. When the mass loading is sufficiently high – or the magnetic field induced by the pickup current – an induced magnetosphere builds up and deviates the particles from the planetary surface. Ionospheres based on H^+ and O^+ diverge mostly at intermediary state, and magnetospheres induced by either ionized hydrogen or ionized oxygen only differ in size by a small percentage.

2. Model and methodology

2.1. The AIKEF simulation code

The results presented in this paper were produced using AIKEF, based on the hybrid model. It is based on the curvilinear code by Bagdonat and Motschmann (2002b). Subsequent development and details of the simulation code such as the particles merging and splitting process, or boundary conditions are provided in Mueller et al. (2011). Hybrid model simulations are based on three major assumptions: the electrons are considered massless (thus fluid), the displacement current is neglected, and the medium is quasi-neutral. Applied to Maxwell's equations, this leads to the general Ohm's law. The ions motions are individually described by their momentum equation, which consists in the Lorentz force. More details are available in the numerous studies which have successfully treated solar system planets such as Mercury (Mueller et al., 2012; Wang et al., 2010), Venus (Martinecz et al., 2009), Mars (Boesswetter et al., 2004). AIKEF was also used to model satellites such as Enceladus (Kriegel et al., 2009, 2011), Tethys (Simon et al., 2009), Titan (Mueller et al., 2010; Simon et al., 2006), Rhea (Roussos et al., 2008; Simon et al., 2012), the Moon (Wiehle et al., 2011; Wang et al., 2011).

Table 1
Normalizations formulas used in our simulations. An example with Earth's typical upstream parameters is provided. The terms m_p and e are the mass of the proton and the elementary charge, respectively. In this paper, $B_0=B_{IMF}$, $n_0=n_{sw}$, $q_0=q_{sw}$, and $m_0=m_{sw}$ (with B_{IMF}, n_{sw}, q_{sw}, and m_{sw} are the upstream stellar wind magnetic field magnitude, number density, particle charge, and particle mass, respectively), i.e., the normalization is made using the upstream stellar wind parameters. The term $v_{A,0}$ stands for the Alfvén velocity.

Quantity	Variable	Normalization	Example
Magnetic field	B	B_0	5.0 nT
Number density	n	n_0	5.0 cm^{-3}
Mass	m_α	m_0	1.0 m_p
Charge	q_α	q_0	1.0 e
Time	t	$t_0=m_0/(q_0B_0)$	2.1 s
Length	x	$x_0=(m_0/\mu_0 {q_0}^2 n_0))^{1/2}$	$1{\cdot}10^2$ km
Velocity	u	$u_0=x_0/t_0=B_0/(\mu_0\rho_0)^{1/2}=v_{A,0}$	48 km/s
Current density	j	$j_0=q_0\ n_0\ v_{A,0}$	3.9 nA/m^2
Electric field	E	$E_0=v_{A,0}\ B_0$	2.4×10^{-4} V/m
Resistivity	η	$\eta_0=E_0/j_0$	$6.2{\cdot}10^3$ Ω m
Pressure	P	$P_0={B_0}^2/(2\ \mu_0)$	$9.9{\cdot}10^{-3}$ nPa
Ion Production rate	Q	$Q_0=n_0\times{}_0^3/t_0$	$2.9{\cdot}10^{21}\ s^{-1}$

The quantities presented in this paper are normalized following Table 1. All quantities (first and second columns) can be formulated using the magnetic field, the number density, the particle charge, and the particle mass. We choose to present the simulation results in normalized quantities to unify all efforts in a self-consistent, non-body-specific approach. We provide a normalization table for any a posteriori comparison (third column of Table 1, with the expressions pertaining to this paper. An illustration of typical parameters at Earth is given in the fourth column of Table 1.

The simulation domain geometry is comparable to that of our earlier study (Vernisse et al., 2013). The upstream plasma flows along the +x-axis and the IMF is oriented along the −z-axis. The resolution of the simulation domain obtained for this work is as follow: the box consists of $400x_0$, where x_0 is the ion inertial length (see Table 1 for definition) along each axis, divided into 128 blocks. The center of the obstacle is taken at the origin of the coordinate system, and is situated at the center of the y and z-axis, and at one third of the x-axis. The radius of the obstacle is $20x_0$.

We use a static mesh with two level of refinement. The first level of refinement is a box extending from $-80x_0$ to $+200x_0$ along the x-axis, from $-70x_0$ to $+70x_0$ along the y and z axe. The second level of refinement extends from $-60x_0$ to $+200x_0$ along the x-axis and from $-50x_0$ to $+50x_0$ along the y and z axe. The resolution of the finest cell is about $1\times{}_0$. A particle splitting and merging procedure is implemented (Mueller et al., 2011) in order to keep a number of 100 particle per cell in average. We note that the finest resolution is sufficient for a correct modeling of the dayside structures of the interaction region such as the bow shock and the plasmapause, which strongly depends on the numerical dissipation in simulations.

The resistivity of the obstacle has been thoroughly discussed in our precedent study (Vernisse et al., 2013). The same resistivity profile has been used in this study. The obstacle is considered as a highly resistive body, but not a perfect insulator.

2.2. Ionosphere modeling and parameters

We implement a Chapman profile to model an ionosphere at the surface of the obstacle in our simulations. We do not discuss the technical part of that model which is already well described in the literature (Baumjohann and Treumann, 1996). The Chapman profile can be summarized by its expression, which represents the probability of generating an ion at a point in the spatial domain: