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Simulations of stellar winds and planetary bodies: Magnetized obstacles in a super-Alfvénic flow with southward IMF

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ABSTRACT

This study addresses the issue of the electromagnetic interactions between a stellar wind and planetary magnetospheres with various dipole field strengths by means of hybrid simulations. Focus is placed on the configuration where the upstream plasma magnetic field is parallel to the planetary magnetic moment (also called "Southward-IMF" configuration), leading to anti-parallel magnetic fields in the dayside interaction region. Each type of plasma interaction is characterized by means of currents flowing in the interaction region. Reconnection triggered in the tail in such configuration is shown to affect significantly the structure of the magnetotail at early stages. On the dayside, only the magnetopause current is observable for moderate planetary dipole field amplitude, while both bow-shock and magnetotail currents are identifiable downtail from the terminator. Strong differences in term of temperature for ions are particularly noticeable in the magnetosheath and in the magnetotail, when the present results are compared with our previous study, which focused on "Northward-IMF" configuration.

1. Introduction

Interactions between celestial bodies and the upstream stellar wind encountered in nature, in particular in our Solar system, can take various forms. From inert obstacles to highly complex giant magnetospheres, these interactions types differ both in mechanisms and in scales. The planets of the Solar System provide a unique laboratory for this study, but, although quite diverse, only show a limited number of types of interactions. Extrapolations to different regimes of interaction were performed to complete our current picture.

Omidi et al. (2002, 2004) used the pressure balance in term of ion skin depth (x_0) to characterize the interaction between a magnetized asteroid and an upstream solar wind, and found that for $x_0 > 1$, a standing fast magnetosonic bow wave is visible upstream, and a slow magnetosonic wake is present in the nightside. Similarly, Trávníček et al. (2003) emphasized the importance of the kinetic modeling for mini-magnetosphere and the formation of shocklet structures. Furthermore, Trávníček et al. (2007) conducted a study using different impinging plasma pressure on the magnetosphere of Mercury, and showed results similar to MagnetoHydroDynamic (MHD) simulation and kinetic effect such as the formation of a ring current close to the planet. A classification of the interaction types was proposed by Barabash (2012), regrouping Solar System obstacles objects by magnetic moment and atmospheric density. However, their classification did not take into account the upstream plasma properties, which modify dramatically the interaction type. Dedicated extrapolations have been performed on inert obstacles (Vernisse et al., 2013), magnetized obstacles with parallel magnetic fields at the subsolar point (Vernisse et al., 2017a) and obstacles unmagnetized but possessing an ionosphere (Vernisse et al., 2017b).

In "Northward-IMF" (Interplanetary Magnetic Field) configuration, the planetary magnetic field and the upstream IMF are parallel at the subsolar point. The resulting double lobe reconnections hardly permit entry of solar wind particles into the magnetosphere. On the other hands, Interactions between an upstream plasma flow and a body whose planetary magnetic field is anti-parallel to the IMF at the subsolar point (or "Southward-IMF" configuration) (Trattner et al., 2007) are subject to a

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strong coupling between the interplanetary medium and the planetary field with strong particle exchanges at the magnetopause. Such a configuration also implies reconnection in the magnetotail, and plasma acceleration and heating on the nightside. In this paper, we investigate how the particle heating influences the structure of the magnetosphere with comparison between "Northward-IMF" (also called "closed magnetosphere") and "Southward IMF" (also called "open magnetosphere"). We analyze the currents in the plasma in order to study the characteristics of the evolution of the magnetosphere.

Currents in magnetized plasma can be effectively used as markers to illustrate the magnetic field distribution, and the associated physical processes (Mauk and Zanetti, 1987). For a detailed description of current identification used in this paper, the reader is referred to the methodology provided in Appendix B. Currents in the Earth's magnetosphere have been studied in detail in the refereed literature (e.g., Ganushkina et al., 2015; Milan et al., 2017), but are still not fully mapped (Liemohn et al., 2016). Beyond Earth, our understanding of currents systems of mini-magnetospheres is far from complete, due to a significant lack of available data. To date, only the MESSENGER spacecraft provides a relatively complete coverage of the mini magnetosphere of Mercury. This discussion emphasizes the need for simulations studies to improve our understanding of magnetoplasmas.

In the next sections, we introduce the model used for this study, present the results from our simulations, and provide a detailed analysis of the results. In particular, we establish four stages corresponding to four types of plasma interactions depending on the strength of the planetary magnetic moment, which parameters are introduced hereafter.

2. Model formulation

2.1. AIKEF (Adaptive Ion Kinetic Electron Fluid) model

The overarching goal of our recent studies has been to establish a full classification of the various types of interactions between upstream plasma and celestial bodies. While Vernisse et al. (2013) focus on unmagnetized, airless bodies in super- and sub-Alfvénic velocities, Vernisse et al. (2017a) focus on airless but magnetized bodies in super- and sub-Alfvénic regimes. Ultimately, in a following paper, Vernisse et al. (2017b) turned to unmagnetized but ionosphere-rich bodies in a super-Alfvénic regime.

The only way to conduct studies with so many parameters is to use a normalization in order to reduce the problem to a minimum number of independent or free parameters. The normalization we use is summarized in the formulae presented in Table 1. The free parameters are the magnetic field magnitude B_0, the particle density n_0, the particle charge q_0, and mass m_0. For simplicity, those parameters are taken equal to the upstream flow parameters, with: $B_0=B_{IMF}$, $n_0 = n_{SW}$, $q_0 = q_{SW}$, and $m_0 = m_{SW}$, where B_{IMF}, n_{SW}, q_{SW}, and m_{SW} represent the magnetic field magnitude, the density, charge, and mass of the upstream stellar wind particles typically measured near Earth, respectively. Therefore, by default the reference or "0'' quantities describe the plasma ahead of the obstacle ("upstream"). The normalization of the other quantities straightforwardly follows from those four upstream plasma parameters. Therefore, a full description of the types of plasma interactions is achieved through this initial parameter based normalization, without loss of generality.

Table 1
Normalization scheme used for all simulations presented in this work.

Quantity	Variable	Normalization	Example of normalization
Magnetic field	B	B_0	5.0 nT
Number density	n	n_0	$5.0\,cm^{-3} = 5.0 \times 10^6 m^{-3}$
Mass	m_α	m_0	$1.0\,m_p = 1.67 \times 10^{-27}$kg
Charge	q_α	q_0	$1.0\,e = 1.60 \times 10^{-19}$C
Time	t	$t_0 = m_0/(q_0 B_0)$	2.1 s
Length	x	$x_0 = (m_0/(\mu_0 q_0^2 n_0))^{1/2}$	1.10^2 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	$\eta_0 = E_0/j_0$	$6.2.10^3$ Ωm
Pressure	P	$P_0= B_0^2/(2\,\mu_0)$	$9.9.10^{-3}$ nPa
Magnetic Moment	M	$M_0 = 4\pi B_0 x_0^3/\mu_0$	$5.3.10^{13}$ A.m^2

For all simulation runs presented in this paper, we used a three-dimensional hybrid model code named AIKEF, which stands for Adaptive Ion Kinetic Electron Fluid. The AIKEF code is based on the former curvilinear code of Bagdonat and Motschmann (2002a), and has been further parallelized by Mueller et al. (2011), who also introduced an adaptive mesh. Specifications of the AIKEF code have been extensively discussed in the literature and will therefore not be repeated here. However, we shall briefly recall that AIKEF has been successfully applied for investigating the magnetized planet Mercury (Wang et al., 2010; Mueller et al., 2012), inert obstacles such as Earth's moon and Rhea (e.g. Wiehle et al., 2011; Simon et al., 2012). AIKEF was equally successfully used to investigate ionosphere rich obstacles such as Enceladus (e.g. Meier et al., 2015), or Titan (e.g. Feyerabend et al., 2016) and comets (e.g. Koenders et al., 2015).

2.2. Simulations parameters

All simulations presented in this paper are initialized as follow. The upstream plasma velocity is taken equal to 8 Alfvén Mach ($M_A = 8$), which is a typical value at Earth. The orientation of the IMF (denoted B_{SW}) is taken along $-\hat{z}$. The upstream stellar wind flows along the +x-axis. The planetary magnetic moment is parallel to the IMF, along $-\hat{z}$, leading to an "open magnetosphere" configuration. The plasma beta is initially set to $\beta_i = 0.5$ for the ion, and $\beta_e = 0.5$ for the electrons. The simulation domain is 600 x_0, 300 x_0, 400 x_0 (1 x_0 = 1 inertial length, as specified in Table 1) along the x-, y-, and z-axes, respectively. The x, y, and z-axes are divided into 144, 96, and 96 cells, respectively. We use a static mesh centered on the interaction region, with two level of refinement (i.e., the mesh remains unchanged throughout the entire duration of the simulation). The finest mesh resolution (about 1 x_0) spans in a 3D rectangular box, with a lower left corner at ($-40x_0$, $-30x_0$, $-30x_0$) and an upper right corner at ($200x_0$, $30x_0$, $30x_0$). A coarser domain, with half the resolution, serves as a buffer between the finest and coarsest region. It occupies the spaces between the lower corners at ($-60x_0$, $-50x_0$, $-50x_0$) and upper corner at ($300x_0$, $50x_0$, $50x_0$), with the exclusion of the inner domain. The resolution is halved again between this intermediate grid and the outermost part of the simulation domain. The mean number of macro-particles per cell is set to 100. The obstacle is represented by a sphere having a radius of $20x_0$. Macro-particles are deleted when crossing the boundary of the obstacle. The magnetic field is propagated into the obstacle by a finite conductivity of 200 η_0, smoothed on the boundary by a power law (see Appendix A for details).

In this paper, we focus on the effects of the magnitude of the intrinsic magnetic dipole moment of the celestial body on the type of plasma interaction. Specifically, we simulate various dipole moment from 100 M_0–500.10^3 M_0 (Table 1). To illustrate our normalization, let us consider the example of Mercury's magnetization. This planet encounters a typical upstream solar wind density (n_{SW}) and magnetic field (B_{SW}) equal to 30 cm^{-3} and 20 nT, respectively, i.e., 6n_0 and 4B_0 using example of normalization scheme provided in Table 1. The same table gives the value $M_0 = 5.3.10^{13}$ A.m^2 if $q_0 = 1.60 \times 10^{-19}$C and $m_0 = 1.67 \times 10^{-27}$kg. Since the magnetic moment of Mercury has been evaluated to be about $M = 1.5\ 10^{13}$ A.m^2 (Mueller et al., 2012), this yields a normalized moment $M = 130 \times 10^3 M_0$. Using the same normalization scheme, Earth encounters upstream plasma parameters