Planetary and Space Science 137 (2017) 40–51

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Stellar winds and planetary bodies simulations: Magnetized obstacles in super-Alfvénic and sub-Alfvénic flows

Y. Vernisse[f,g,*], J.A. Riousset[e], U. Motschmann[a,d], K.-H. Glassmeier[b,c]

[a] Institute for Theoretical Physics, T.U. Braunschweig, Germany
[b] Institute for Geophysics and Extraterrestrial Physics, T.U. Braunschweig, Germany
[c] Max Planck Institute for Solar System Research, University of Göttingen, Germany
[d] Institute for Planetary Research, D.L.R. Berlin, Germany
[e] Embry Riddle Aeronautical University, Daytona Beach, FL, United States
[f] Institut de Recherche en Astrophysique et Planétologie, Toulouse, France
[g] Université Paul Sabatier, Toulouse, France

ARTICLE INFO

Keywords:
Hybrid simulation
Planetary dipole
Plasma interaction
Currents
Space physics

ABSTRACT

Most planetary bodies are moving in the solar wind, in a stellar wind, or in a plasma flow within the magnetosphere of a planet. The interaction of the body with the flowing plasma provides us with various interaction types, which mainly depend on the flow speed, the magnetization of the body, its conductivity, the presence of an ionosphere, and the size of the body. We establish two cornerstones representing highly magnetized obstacles embedded in a super-Alfvénic and sub-Alfvénic plasma. Those two cornerstones complete the two cornerstones defined in our previous study on inert obstacles in super-Alfvénic and sub-Alfvénic regimes. Tracking the transitions between these cornerstones enable better understanding of the feedback of the obstacle onto the plasma flow. Each interaction is studied by means of the hybrid model simulation code AIKEF. The results are summarized in three dimensional diagrams showing the current structures, which serve as a basis for our descriptions. We identify the major currents such as telluric, magnetosonic, Chapman–Ferraro, and bow-shock currents as the signatures of the particular state of development of the interaction region. We show that each type of interactions can be identified by studying the shape and the magnitude of its specific currents.

1. Introduction

Planetary objects possessing an internal magnetic moment are studied in the Solar System through Mercury, Earth, the giant planets and Ganymede. There have been numerous studies on the impact of the solar wind on magnetospheres induced by an intrinsic planetary magnetic moment (Kivelson and Bagenal, 2007, and references therein). These focus in particular on the effect of the solar wind velocity in terms of Alfvén Mach number (e.g. Roelof and Sibeck, 1993; Shue et al., 1997; Lavraud et al., 2013). The planets of the Solar System are standing most of the time in a super-Alfvénic solar wind with velocities from 300 to 1000 km/s (Marsch, 2006). Interactions of a sub-Alfvénic solar wind with a planetary obstacle are rare, and only occur during particular events, such as coronal mass ejections (Chané et al., 2012). However, moons embedded in the magnetosphere of their host planets are mostly subjected to a sub-Alfvénic inflowing plasma. Nonetheless, one moon, Ganymede – embedded in the magnetosphere of Jupiter – has been proven to have an intrinsic dipole field (Kivelson et al., 1996). Several studies focus on those two parameters – the Solar wind Alfvén Mach number and planetary intrinsic field – and their influences, e.g. on the magnetopause position (Case and Wild, 2013), the reconnection rate (Borovsky, 2008), or global and topological studies (Gombosi et al., 2000; Ridley, 2007; Tsyganenko and Andreeva, 2015). Analysis has been performed using a range of magnetizations as a main parameter, with the purpose of describing the evolution of the magnetosphere as a function of the internal dipole strength and the inflowing plasma Mach number. Omidi et al. (2002, 2004) and Simon et al. (2006a) conducted such studies for simulations of an asteroid using various magnetic moments, while Boesswetter et al. (2004, 2007, 2010) and Kallio et al. (2008) simulated the time evolution of the now extinct Martian intrinsic dipole. Such extrapolations of interaction types have been performed using different parameters, in order to evaluate the magnetic field of extrasolar planets (Durand-Manterola, 2009), their signatures on a host star (Saur et al., 2013), or their potential observation (Farrell et al., 1999; Zarka, 2006). Electric current signatures in the magnetosphere have been extensively investigated via both simulations and

* Corresponding author at: Institute for Theoretical Physics, T.U. Braunschweig, Germany.
E-mail address: yoann.vernisse@irap.omp.eu (Y. Vernisse).

http://dx.doi.org/10.1016/j.pss.2016.08.012
Received 10 March 2015; Received in revised form 20 June 2016; Accepted 2 August 2016
Available online 23 January 2017
0032-0633/

observations (e.g. Siscoe et al., 2000; Liemohn et al., 2013). Describing the current system is a convenient way to attach the topology of magnetosphere to its fundamental processes (Mauk and Zanetti, 1987). Magnetospheric permanent current systems that have been listed are the ring, tail, Chapman–Ferraro, field aligned and ionospheric currents (Ganushkina et al., 2015, and references therein). In this paper, we analyze various current systems as a function of the upstream plasma Alfven Mach number, and planetary intrinsic magnetic moment. We base our study on the interpretation of the results from the hybrid model code AIKEF. This paper is a continuation of Vernisse et al. (2013). First we explain how we identify the current systems from the simulation results, then we will summarize those systems into schematics. Details of simulations results are provided in the auxiliary material, where all aspects pertaining to the interpretation are introduced in detail.

2. The AIKEF simulation code

2.1. Model description

Hybrid models are a good compromise in plasma simulation between needs in computational time and physical description. For our study we use a 3-D particles-in-cell simulation based on the hybrid model: AIKEF. This stands for Adaptive Ion Kinetic Electron Fluid and it is based on the work by Bagdonat and Motschmann (2002a). Subsequent improvement have been developed and described by Mueller et al. (2011). The hybrid model treats electrons as a fluid and ions as particles. Three assumptions are applied when deriving the hybrid model equations: (1) quasi-neutrality, (2) masslessness of electrons, and (3) negligibility of the displacement current. The motion of each ion is derived using the momentum equation dominated by Lorentz's force. The AIKEF code has already shown its sturdiness to reproduce observations data, through simulations of the Moon (Wiehle et al., 2011; Wang et al., 2011) with data from ARTEMIS, Mercury (Wang et al., 2010; Mueller et al., 2012) with data from Messenger, Rhea (Roussos et al., 2008; Simon et al., 2012), Enceladus (Kriegel et al., 2009, 2011), Tethys (Simon et al., 2009) and Titan (e.g. Mueller et al., 2010; Simon et al., 2006b) with data from the Cassini spacecraft. The numerical challenges and techniques pertinent to AIKEF have been discussed in Mueller et al. (2011).

2.2. Simulation parameters

In this paper the results are presented and discussed using normalized quantities. The normalizations of the relevant quantities related to this work are described in Table 1. The average number of particle in each cell is 100. Also, particles start to split and merge 8 cells away from the boundary of the refined area in order to avoid artificial gradient (Mueller, 2011). The fundamental quantities, B_0, n_0, q_0, and m_0, are taken equal to the upstream plasma magnetic field, number density, particle charge, and particle mass, respectively. The other normalization factors naturally follow from the normalization procedure and can be expressed as functions of the above quantities. An example for each quantity is given for Earth-like upstream solar wind parameters in the last column. The reader is invited to refer to this table to convert the normalized results with the appropriate upstream parameters. Other fixed plasma parameters in this paper are ion plasma beta at initialization $\beta_i = 0.5$; electron plasma beta $\beta_e = 0.5$; planetary radius $R_p = 20x_0$, where the ion inertial length x_0 is defined in Table 1; and the planetary resistivity $\eta_p = 200\eta_0$. The radius is chosen to correspond to a Lunar-sized obstacle considering the upstream plasma parameters around the Moon, while the resistivity is set with the purpose of having a quasi-dielectric obstacle, in consistency with our previous study (Vernisse et al., 2013). All but two parameters are fixed for every simulation. Our variables are listed in Table 2, which consist in: (1) the magnitude of the internal magnetic moment of the obstacle and (2) the upstream stellar wind velocity. The ratio between the upstream velocity and the magnetic moment is illustrated by the stand-off distance which is expressed by:

$$L_{SO} = \left(\frac{4B_{surf}^2}{B_{up}^2 + 0.88\mu_0 m_{up} n_{up} v_{up}^2} \right)^{1/6}, \quad (1)$$

with B_{surf} being the magnetic field magnitude from the planetary magnetic moment at (x = $1R_p$, y = 0, z = 0). The terms B_{up}, m_{up}, n_{up} and v_{up} are the magnetic field, particle mass, number density, and the velocity of the stellar wind, respectively. In super-Alfvénic regimes, the dynamic pressure of the upstream plasma is higher than its magnetic pressure, but in sub-Alfvénic regime, the upstream magnetic field pressure is dominant. Since both regimes are treated in this paper, the upstream field term has been added in the stand-off distance equation (see details in Baumjohann and Treumann, 1996). The scenarios investigated in this work are listed in Table 2. They are identified by a name providing the normalized magnetic moment with its orientation and the upstream velocity in Alfvén Mach. Each set of

Table 1
Table of normalizations with a typical set of values at Earth. The terms m_p and e are the mass of the proton and the elementary charge, respectively. One should note that the expressions here are written without any simplifications. A common simplification is to consider: $m_0 = m_p$ and $q_0 = e$. In this paper, we consider that $B_0 = B_{up}$, $n_0 = n_{up}$, $q_0 = q_{up}$, and $m_0 = m_{up}$ (with B_{up}, n_{up}, q_{up}, and m_{up} being 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[a]	Example
Fundamental quantities			
Magnetic field	B	B_0	5.0 nT
Number density	n	n_0	5.0 cm^{-3}
Mass	m_α	m_0	1.0m_p
Charge	q_α	q_0	1.0e
Secondary quantities			
Time	t	$t_0 = m_0/(q_0 B_0)$	2.1 s
Length	x	$x_0 = (m_0/(\mu_0 q_0^2 n_0))^{1/2}$	$1.0 \cdot 10^2$ 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	$E_0 = v_{A,0} B_0$	$2.4 \cdot 10^{-4}$ V/m
Resistivity	η	$\eta_0 = E_0/j_0$	$6.2 \cdot 10^3$ Ω m
Magnetic moment	M	$M_0 = 4\pi B_0 x_0^3/\mu_0$	$5.3 \cdot 10^{13}$ A m^2

[a] With appropriate definition when necessary.

Table 2
Simulation parameters for the runs presented in this paper. The magnetic moments, surface magnetic field magnitudes, and velocities are normalized using Table 1. The term B_{surf} refers to the magnitude of the planetary field at ($x = 1R_p$, 0, 0), v_{up} is the upstream plasma velocity, and L_{SO} refers to the stand-off distance, which expression is detailed in Section 2 and given by Eq. (1). The name of each case gives the orientation ($+\hat{z}$) and magnitude of the magnetic moment of the obstacle, and the upstream velocity of the stellar wind.

Case name	M [M_0]	B_{surf} [B_0]	v_{up} [$v_{A,0}$]	L_{SO} [R_p]	Figures
Cornerstones					
$+80\text{E}3M_0\hat{z}\vert 8v_{A,0}$ (Mercury-Type)	$80 \cdot 10^3$	10	8	1.38	1,2
$+40\text{E}3M_0\hat{z}\vert 0.5v_{A,0}$ (Ganymede-Type)	$40 \cdot 10^3$	5	0.5	2.08	3
Transitions					
$+10\text{E}3+10\text{E}3M_0\hat{z}\vert 8v_{A,0}$	$10 \cdot 10^3$	1.25	8	0.69	4
$+5\text{E}3M_0\hat{z}\vert 2v_{A,0}$	$5 \cdot 10^3$	0.62	2	0.84	5
$+40\text{E}3M_0\hat{z}\vert 2v_{A,0}$	$40 \cdot 10^3$	5	2	1.68	6
$+5\text{E}3M_0\hat{z}\vert 1v_{A,0}$	$5 \cdot 10^3$	0.62	1	0.97	7a
$+40\text{E}3M_0\hat{z}\vert 1v_{A,0}$	$40 \cdot 10^3$	5	1	1.94	7b