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Stellar winds and planetary bodies simulations: Lunar type interaction in super-Alfvénic and sub-Alfvénic flows

Y. Vernisse [a,b,c,*], H. Kriegel [a], S. Wiehle [a], U. Motschmann [a,d], K.-H. Glassmeier [b]

[a] Institute for Theoretical Physics, TU Braunschweig, Germany
[b] Institute for Geophysics and Extraterrestrial Physics, TU Braunschweig, Germany
[c] Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany
[d] DLR-Institute for Planetary Research, Berlin, Germany

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ABSTRACT

Exoplanets are a place of numerous new effects in plasma physics and raise interest in extra-solar physics. Mainly specific cases of plasma interaction between planets, moons and the solar wind have been studied up to now, using data from observations within our solar system. A systematic description of the plasma interactions with respect to the properties of the stellar wind has not been made yet. In order to begin a systematization of the interactions, we study the lunar type plasma interaction by means of the A.I.K.E.F. simulation code, based on the hybrid model. By numerical derivation of MHD wave mode propagation, we show that the lunar wake expansion is governed by the MHD modes. Furthermore, the wake structure can be described by analyzing the different types of currents flowing around the lunar wake and assigning each current to the modes triggered by the obstacle. We show that most of the currents present in the lunar type interaction are a diamagnetic or a polarization current. This method has been also applied for results concerning the evolution of the lunar plasma structure by modifying the upstream velocity, with a transition from a super-Alfénic velocity to a sub-Alfvénic regime. The stellar wind transition study shows that the current switches from a horizontal structure where the current is mostly concentrated in the equatorial plane to a vertical structure where the current is mostly distributed along the magnetic field lines.

1. Introduction

Since the first exoplanet orbiting a Sun-type star was detected in 1995, the field is broadening and the amount of data is constantly increasing (Schneider, 1995). While missions like Kepler and Corot increase the number of detected planets, other project using radiometry (Farrell et al., 1999) try to measure local properties of stellar systems and in particular, extrasolar magnetospheres. Those projects have proven that extra solar systems are far different from our solar system and are a place of various new types of plasma interactions between the stellar wind and the planets. Properties of plasma interactions are dependent of several general parameters which are the stellar wind velocity, the presence, strength and orientation of a planetary dipole field, the presence and strength of an ionosphere, the ion and electron betas and the obstacle radius. In this parameter space, the points which have been studied are mostly derived from objects within our solar system. Up to now, only few studies on the transition between different parameters have been carried out: Omidi et al. (2004) and Simon et al. (2006a) started the analysis of the effect of a dipole field on an asteroid, taking interest in the transition between different magnetic dipole strengths. Boesswetter et al. (2004, 2007, 2010) and Kallio et al. (2008) studied the interaction with the Martian magnetic field including the possible variation of the dipole field through time. The evolution of an ionosphere has been studied for the case of a comet approaching the sun, which increases the ions production rate (Bagdonat and Motschmann, 2002b; Gortsas et al., 2010). Saur et al. (2013) studied the case of sub-Alfvénic interaction for moon–planet interaction and planet–star interaction by calculating the Poynting flux to derive the energy of the triggered Alfvén wings and their footprints on the host star or planet. In order to explore how planetary interaction regions develop under the influence of different upstream plasma regimes that extrasolar planet may be subject to, we carry out hybrid simulations with the A.I.K.E.F. code. In this paper we present one point of the parameter grid: the case of the Earth's moon, and the evolution of the plasma interaction along one axis of the parameter space: the stellar wind velocity.

Although a thin exosphere has been detected at the surface of the Moon (Tanaka et al., 2009) and its importance evaluated for

* Corresponding author at: Institute for Theoretical Physics, TU Braunschweig, Mendelssohnstrasse 3, 38106 Braunschweig, Tel.: +49 53 13915178.
E-mail address: y.vernisse@tu-bs.de (Y. Vernisse).

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the asymmetry in the Mach cone due to the mass loading (Lipatov et al., 2012), the Earth's moon lacks both a global ionosphere and magnetic field. Therefore, as the particles carried by the solar wind hit the surface of the Moon, they are absorbed, leaving a wake in the plasma. The behaviour of the plasma in the interaction between the solar wind and the Earth's Moon has been described starting in the early time of space exploration with measurement by Lunar Explorer 35 (Ness et al., 1967) and is still ongoing. Several theoretical models were developed taking into account the magnetosonic mode triggered by the Moon and their interaction in the plasma (Whang, 1968a, 1968b; Catto, 1974; Trávníček et al., 2005). The presence of sonic rarefaction modes has already been demonstrated (Samir et al., 1983), triggering a diamagnetic current in the center in the wake. In this paper we emphasize the role of MHD modes as triggering polarization current around the wake. Parts of the currents system have been described by Owen et al. (1996). Zhang et al. (2012) have explored the existence of fast magnetosonic waves triggered by the Moon. The Moon has also been studied by means of simulation with drift-kinetic model (Lipatov et al., 2005), hybrid models (Kallio, 2005) and full particle model (Birch and Chapman, 2001). Presentation and overview of different models has been done by Lipatov (2002). Recent studies have involved investigations of the effects of the interplanetary magnetic field (IMF) angle (Wang et al., 2011), the current system and its evolution with the IMF angle (Fatemi et al., 2013), comparison with WIND data (Holmström et al., 2012) and ARTEMIS data (Wiehle et al., 2011). A summary of studies on the Moon is given by Halekas et al. (2011) who present the most recent answers to questions such as the effect of the cavity behind the Moon and ions entering the wake.

However, we expand these studies by deriving a more general current system that can be applied to any set of parameters and study the effect of the upstream velocity on the wake structures. We construct such a model by using the currents to identify each interaction. The currents provide information about the configuration of the magnetic field and help to create a consistent picture of the plasma structures by separating currents in different kinds. Those kinds are polarization current, diamagnetic current and induction current. Furthermore, we establish a model using magnetosonic modes triggered at the surface in the meridional plane of Moon and carried by the solar wind. Our purpose is to connect the magnetosonic modes and the currents in a consistent way. This method was investigated by Bale et al. (1997) and Wiehle et al. (2011). Since the magnetosonic modes can be derived from the parameters in a stationary situation, relying on the currents connected to the waves is helpful to derive a continuous variation between two arbitrary points of the parameter space: i.e. knowing how the waves propagation evolves with the modification of the upstream velocity allows us to derive the current system for any upstream velocity within the values which have been studied.

Once this starting point is established, we can choose several ways determined by the plasma or obstacle parameters chosen to be varied. In this paper, we modify the Lunar plasma interaction configuration by decreasing the upstream velocity from the super-Alfvénic interaction to a sub-Alfvénic interaction. sub-Alfvénic plasma interactions are present in our solar system for the case of the airless satellites of Jupiter and Saturn which are orbiting inside each magnetosphere, respectively. Differences between sub-Alfvénic regime and trans-Alfvénic regime have been studied for Rhea and Tethys (Khurana et al., 2008). But the transition of the structures between a super- and sub-Alfvénic interaction has not been investigated before. We then apply the description created from the Lunar case study to the stellar wind velocity transition and confirm the evolution of current structures connected to the magnetosonic modes.

This work is divided into three main parts, at first we describe the A.I.K.E.F. code that we used for our study. Next we present the results obtained from the simulations of the Moon case at first and continue with the stellar wind velocity transition. Afterward we discuss the structure of the plasma interaction with the Moon and then its evolution by stellar wind velocity modification.

2. The A.I.K.E.F. code

For this study, we use the three dimensional simulation particles in cell code called A.I.K.E.F. (Adaptive Ion Kinetic Electron Fluid) based on the hybrid model.

2.1. The hybrid model

The A.I.K.E.F. code has been developed and fully described by Mueller et al. (2011) and is based on the code from Bagdonat and Motschmann (2002a). It has already been applied to the Moon (Wiehle et al., 2011; Wang et al., 2011), Mercury (Mueller et al., 2012; Wang et al., 2010), 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 successful results. Hence, it has proven its ability to describe many types of obstacles and upstream conditions, making it an efficient tool for our study. Therefore, we will summarize the description of the hybrid model. The hybrid model is an approach of the plasma equations describing electrons as a fluid and ions as particles. The field equations are derived by using Maxwell's equations and momentum conservation with three basic assumptions, which are quasi neutrality, $n_e = n_i = n$, mass-less electrons $m_e = 0$, and neglection of the displacement current $\epsilon_0\, dE/dt \ll j$. This leads to

$$\vec{E} = -\vec{u}_i \times \vec{B} + \frac{(\vec{\nabla} \times \vec{B}) \times \vec{B}}{\mu_0 ne} + \eta \frac{\vec{\nabla} \times \vec{B}}{\mu_0} - \frac{\vec{\nabla} P_e}{ne} \quad (1)$$

and Faraday's law gives

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{u}_i \times \vec{B}) - \vec{\nabla} \times \frac{(\vec{\nabla} \times \vec{B}) \times \vec{B}}{\mu_0 ne} - \vec{\nabla} \times \left(\eta \frac{\vec{\nabla} \times \vec{B}}{\mu_0} \right) \quad (2)$$

where $\vec{u}_i$ is the ion bulk velocity, $\vec{B}$ is the magnetic field, $\vec{E}$ the electric field, n the density, e the elementary charge, P_e is the electron pressure, η is the resistivity and μ_0 is the permeability of free space. The motion of the ions is governed by the Lorentz force, and the electron pressure follows an adiabatic law.

2.2. Numerical aspects

The length scale chosen for our study is the inertial length, or ion skin depth, defined by $x_0 = c/\omega_{p,i0}$ where $\omega_{p,i0}$ is the background ion plasma frequency and c the speed of light. We choose to present the results in such length scale instead of more common units, using the idea of generalization that every result can be transposed to different absolute values of magnetic field and density. However, in order to place our study within the background of the Moon case, we set up the physical properties of our simulation from usual values at Earth. These parameters are summarized in Table 1.

The stellar wind is flowing along the x axis, with $\vec{v}_{sw} = +|\vec{v}_{sw}|\vec{e}_x$, with $|\vec{v}_{sw}| = 390$ km/s, and the interplanetary magnetic field (IMF) is $\vec{B}_{IMF} = -|\vec{B}_{IMF}|\vec{e}_z$, with $|\vec{B}_{IMF}| = 5$ nT. We set $\beta = 0.5$ which corresponds to a temperature of 6.2 eV for ions and electrons. The obstacle is defined in the A.I.K.E.F. code by a volume where particles are deleted when they hit the surface, and where a resistivity is applied, so that the magnetic field is transported as described by the term $\eta \vec{\nabla} \times \vec{B}/\mu_0$ in Eq. (1) (Roussos et al., 2008). We use a resistivity of 6×10^6 Ωm, this leads to a magnetic