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The light (H^+, H_2^+, He^+) and heavy (Na^+) pickup ion dynamics in the lunar-like plasma environment: 3D hybrid kinetic modeling

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Abstract

In this report we discuss the self-consistent dynamics of pickup ions in the solar wind flow around the lunar-like object. In our model the solar wind and pickup ions are considered as a particles, whereas the electrons are described as a fluid. Inhomogeneous photoionization, electron-impact ionization and charge exchange are included in our model. The Moon will be chosen as a basic object for our modeling. The current modeling shows that mass loading by pickup ions H^+, H_2^+, He^+, and Na^+ may be very important in the global dynamics of the solar wind around the Moon. In our hybrid modeling we use exponential profiles for the exospheric components. The Moon is considered as a weakly conducting body. Special attention will be paid to comparing the modeling pickup ion velocity distribution with ARTEMIS observations. Our modeling shows an asymmetry of the Mach cone due to mass loading, the upstream flow density distribution and the magnetic field. The pickup ions form an asymmetrical plasma tails that may disturb the lunar plasma wake.

Keywords: Exospheres; Pickup ions; Induced magnetospheres; Satellites; Plasma modeling

1. Introduction

The hybrid kinetic model used here supports comprehensive modeling of the interaction between different spatial and energetic elements of the Moon-solar wind-magnetosphere of the Earth system. This involves variable upstream magnetic field and solar wind plasma, including energetic ions, electrons, and neutral atoms. This capability is critical to improved interpretation of existing measurements for surface and exospheric composition from previous missions and planning future missions.

Lunar observations show the existence of several species of the neutrals and pickup ions like Na, He, K, O etc., (see e.g., Tyler et al., 1988; Potter and Morgan, 1988; Tanaka et al., 2009; Hartle and Killen, 2006). Hartle and Killen (2006) have provided the measurable lower limits of exosphere densities with currently known upper limits inside exosphere: $n_{Na} = 17 - 70$ cm^{-3}, $n_{He} = 336 - 2000$ cm^{-3}, $n_O = 321 - 500$ cm^{-3}, $n_H = 65 - 17$ cm^{-3}, and $n_{H_2} = 7.6$–9000 cm^{-3}. Recently, MAP-PAGE-IMA (Plasma energy Angle and Composition Experiment, and Ion Mass Analyzer) onboard Japanese lunar orbiter SELENE (KAGUYA) detected Moon originating ions at 100 km altitude. Ion species of H^+, He^{++}, He^+, C^+, O^+, Na^+, K^+, and Ar^+ were definitively identified. The Solar Wind Ion Detectors (SWIDs) on the Chang'E-1 spacecraft, while orbiting the Moon, occasionally observed two continuous flux peaks with energies not exceeding 8 and 4 times that of the prevailing solar wind energy (Wang et al., 2011b).

There is a set of MHD (Wolf, 1968; Spreiter et al., 1970), kinetic (Birch and Chapman, 2001), hybrid (Kallio, 2005; Travnicek et al., 2005; Lipatov and Cooper, 2010; Wang

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et al., 2011a; Holmström et al., 2012; Wiehle et al., 2011), drift kinetic (Whang, 1969; Whang and Ness, 1970; Catto, 1974; Lipatov, 1976; Lipatov, 2002; Lipatov et al., 2005), and electrostatic (Farrell et al., 1998; Tao et al., 2012), and Monte Carlo (Lee et al., 2011) modeling of the lunar plasma environment.

Wave-particle interactions play a very important role in plasma dynamics near the Moon: mass loading, excitation of low-frequency waves and the formation of the non-Maxwellian particle velocity distribution function. Particle-wave interactions play a very important role in the possible formation of an oblique shock wave system inside the lunar plasma wake, and in coupling of pickup ions and the upstream ions via excitation of low-frequency waves. These kinetic processes become important in the formation of an obstacle for the upstream flow.

Magnetohydrodynamic (MHD) models have been useful for the study of the interaction between plasma flow and the Moon (Wolf, 1968; Spreiter et al., 1970). MHD modeling demonstrated a global picture of magnetospheric interaction with the Moon, formation of the plasma wake with external rarefaction waves and oblique shock structures. However, several kinetic effects are not included in the MHD formalism, namely: anisotropy of the ion velocity distribution which results to excitation of the low-frequency electromagnetic waves, formation of the electron and ion beams and excitation of the high-frequency waves, etc. Many of these effects may be recovered by using hybrid or full kinetic modeling.

In papers by Whang (1969), Whang and Ness (1970), and Lipatov (1974, 1975, 1976), they had studied the structure of the lunar plasma wake in the "guiding center" approximation. These models produced the magnetic field perturbations which are in a good agreement with onboard observations of the lunar wake by the Explorer 35 spacecraft. The "guiding center-in-cell" numerical modeling (Lipatov, 1976) also produced the magnetic filed perturbation in the case of nonstationary solar wind and the conducting lunar core. A quasi-MHD (Chew-Goldberger-Low) approach (Chew et al., 1956)) with anisotropic pressure has also described well the electromagnetic perturbations in the lunar wake (Catto, 1974). Several 3D hybrid modeling of the Moon plasma interactions were performed during the last decade as described in papers by Kallio (2005), Travnicek et al. (2005), Lipatov et al. (2005), Lipatov and Cooper (2010), Wang et al. (2011a), and Holmström et al. (2012). These models describe well wave-particle interactions, in particular, the anisotropy of the ion velocity distributions. The hybrid models demonstrate the formation of the oblique shock-like structure in the middle of the lunar wake. The hybrid modeling by Wiehle et al. (2011) has been devoted to an interpretation of the ARTEMIS data and good agreement was produced.

The hybrid kinetic model allows us to take into account the finite gyroradius effects of pickup ions and to correctly estimate the ion velocity distribution and the fluxes along the magnetic field, and on the lunar surface. Modeling shows the formation of the asymmetric Mach cone, the structuring of the pickup ion tails, and presents another type of lunar-solar wind interaction. We will compare the results of our modeling with observed distributions.

In our study the model of the neutral exosphere (H, H_2, He, Na) are chosen from Hartle and Killen (2006). Note, that we already performed the modeling the dynamics of O^+ and (Na^+, He^+) pickup ions near the Moon (Lipatov et al., 2011b; Lipatov et al., 2012a). The solar wind parameters are chosen from the ARTEMIS observations (Wiehle et al., 2011). We apply a time-dependent Boltzmann's "particle-in-cell" approach (Lipatov et al., 1998), together with a hybrid plasma (ion kinetic) model (Lipatov et al., 2002b) in three spatial dimensions (see, e.g. Lipatov and Combi, 2006) using a prescribed but adjustable neutral exosphere and the heavy ion clouds model for the Moon. A Boltzmann modeling is applied to model charge exchange between (incoming and pickup) ions and the immobile exospheric neutrals. In this paper we discuss the results of hybrid kinetic modeling of the lunar environment, namely, global plasma structures, e.g., the formation of the asymmetrical Mach cone, magnetic barrier, pickup ion tails etc. The results of this kinetic modeling are compared with the ARTEMIS flyby observational data. Comparison of results of our hybrid model with other ARTEMIS flybys (Halekas et al., 2011) will be presented in a future publication.

The paper is organized as follows: in Section 2 we present the computational model and a formulation of the problem. In Section 3 we present the results of modeling the plasma environment near the Moon and comparison with observational data. Finally, in Section 4 we summarize our results and discuss the future development of our computational model.

2. Formulation of the problem and mathematical model

To study the interaction of the solar wind with the ionized and neutral components of the lunar environment we use a quasi-neutral hybrid model, namely, a kinetic description for the upstream and pickup ions, and a fluid approximation for electrons. The hybrid model accurately describes wave-particle interactions on the following ion spatial (λ) and time (ω^{-1}) scales: $\lambda \sim \rho_{ci} = U_0/\Omega_i$ or $\lambda \sim c/\omega_{pi}$ and $\lambda \gg \rho_{ce}$; $\omega \leqslant \Omega_i$, where ρ_{ci} and ρ_{ce} denote the gyroradii for ions and electrons (respectively); U_0 is the bulk velocity of the background plasma; c/ω_{pi} denotes the ion inertial length, and Ω_i is the ion gyrofrequency. The length λ may represent either the wave-length of the excited low-frequency waves or the spatial scale of the plasma structures and boundaries in the Lunar environment. The model includes photoionization, electron impact ionization and charge exchange. We explicitly include ionization, mass-loading and charge exchange as the dominant mechanisms for the interaction away from the lower boundary at the Moon. We also include finite conductivity, given by the diffusion scale length, at the inner boundary.