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Effects of multiscale phase-mixing and interior conductance in the lunar-like pickup ion plasma wake. First results from 3-D hybrid kinetic modeling

A.S. Lipatov [a,b,*,1], M. Sarantos [c], W.M. Farrell [c], J.F. Cooper [c,2]

[a] GPHI UMBC/NASA GSFC, Code 673, Greenbelt, MD 20771, USA
[b] Faculty of Problems of Physics and Power Engineering, Moscow Institute of Physics and Technology, Russia
[c] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

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A B S T R A C T

The study of multiscale pickup ion phase-mixing in the lunar plasma wake with a hybrid model is the main subject of our investigation in this paper. Photoionization and charge exchange of protons with the lunar exosphere are the ionization processes included in our model. The computational model includes the self-consistent dynamics of the light (H^+ or H_2^+ and He^+), and heavy (Na^+) pickup ions. The electrons are considered as a fluid. The lunar interior is considered as a weakly conducting body. In this paper we considered for the first time the cumulative effect of heavy neutrals in the lunar exosphere (e.g., Al, Ar), an effect which was simulated with one species of Na^+ but with a tenfold increase in total production rates. We find that various species produce various types of plasma tail in the lunar plasma wake. Specifically, Na^+ and He^+ pickup ions form a cycloid-like tail, whereas the H^+ or H_2^+ pickup ions form a tail with a high density core and saw-like periodic structures in the flank region. The length of these structures varies from 1.5 R_M to 3.3 R_M depending on the value of gyroradius for H^+ or H_2^+ pickup ions. The light pickup ions produce more symmetrical jump in the density and magnetic field at the Mach cone which is mainly controlled by the conductivity of the interior, an effect previously unappreciated. Although other pickup ion species had little effect on the nature of the interaction of the Moon with the solar wind, the global structure of the lunar tail in these simulations appeared quite different when the H_2^+ production rate was high.

1. Introduction

The solar wind plasma, lunar surface regolith, and neutral exosphere are interconnected in complicated ways. The critical processes that influence the structure of the lunar wake and plasma environment are the rate of ion production from the Moon's tenuous atmosphere, the reflection of solar wind particles, the conductivity of the interior, the rate of ions sputtered from the surface, and the formation of the mini-magnetospheres by lunar crustal fields. Although the complete scheme of the solar wind–lunar-like interaction requires all above mechanisms to be included, studying the effect of the dynamics of multiple pickup ion species on the large scale configuration is still of great interest because it can aid the interpretation of ARTEMIS and other mission data. In this paper, we continue to examine the interplay of these environment parameters.

The lunar atmosphere consists of numerous molecular and atomic species which are sources of ions. Earlier observations, as reviewed in Stern (1999) and Lipatov et al. (2013b), showed the existence of exospheric neutrals such as He, Na, K, and O. Detected ion species included $H^+, He^{++}, He^+, C^+, O^+, Na^+, K^+$, and Ar^+ (Tanaka et al., 2009). Many more neutrals are theoretically expected to be released by both solar wind and micrometeoroid vaporization (e.g., Wurz et al. (2007); Sarantos et al. (2012a)). More recently, Lunar Reconnaissance Orbiter (LRO) measurements detected the presence of molecular hydrogen in the atmosphere of the Moon with a surface number density of 1200 ± 400 cm^{-3} (Stern et al., 2013). A molecular hydrogen exosphere with 1200 cm^{-3} at high latitudes would require conversion of 10–50% of the incident solar wind to molecular hydrogen (Hurley et al., 2012). Furthermore, the experiments on board of the Lunar Atmosphere and Dust Environment Explorer (LADEE) provided new information about

* Corresponding author. GPHI UMBC/NASA GSFC, Code 673, Greenbelt, MD 20771, USA.
E-mail addresses: Alexander.Lipatov-1@nasa.gov (A.S. Lipatov), Menelaos.Sarantos-1@nasa.gov (M. Sarantos), William.M.Farrell@nasa.gov (W.M. Farrell), John.F.Cooper@nasa.gov (J.F. Cooper).
[1] *URL:* home page (A.S. Lipatov).
[2] Additional information about the second and third authors.

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noble gases (He, *Ar*, N*e*) (Benna et al., 2015), and detected monthly and semi-annual variations of exospheric potassium and sodium (Colaprete et al., 2016). Last, preliminary detections of other species from LADEE (OH, H_2O, Si, Al, Mg, Ca, Ti, and Fe neutral components) were reported following major meteor showers such as the Geminids (Colaprete et al., 2014). Direct observation of sputtered oxygen from the lunar surface was reported by Energetic Neutral Atom (ENA) measurements from Chandrayaan-1 (Vorburger et al., 2014).

The neutral particle and plasma measurements around the Moon by recent lunar missions – Chandrayaan-1, Kaguya, Chang'e−1, LRO, and ARTEMIS – demonstrated many important plasma processes in the exosphere and the surface of the Moon, namely, a backscattering of the solar wind protons as energetic neutral atoms from lunar surface, sputtering of atoms from the lunar surface (Poppe et al., 2014), and the formation of a “mini-magnetosphere” around lunar magnetic anomaly regions (Kallio et al., 2012; Deca et al., 2014; Zimmerman et al., 2015; Fatemi et al., 2015; Bhardwaj et al., 2015; Halekas, 2017; Usui et al., 2017).

There is a long history of plasma simulations of the lunar environment, as also reviewed in Lipatov et al. (2013b). While magnetohydrodynamic (MHD) models (Wolf, 1968; Spreiter et al., 1970) have been useful for a study of the global configuration of the plasma structures near the Moon, important kinetic effects have not been included in the MHD formalism. These effects include, for instance, the anisotropy of the ion velocity distribution resulting in the excitation of the low-frequency electromagnetic waves, the formation of the electron and ion beams and excitation of the high-frequency waves, and others (see e.g., Winske et al. (1985); Farrell et al. (1998)).

These kinetic effects may be simulated with different degrees of fidelity by using hybrid or full kinetic modeling. The full kinetic models (Birch and Chapman, 2001; Deca et al., 2014; Usui et al., 2017) take into account the effects of the finite electron gyroradius, the electron non-Maxwellian velocity distributions, and charge separation. Hybrid kinetic models (Kallio, 2005; Travnicek et al., 2005; Lipatov and Cooper, 2010; Wang et al., 2011a; Holmström et al., 2012b; Wiehle et al., 2011; Fatemi et al., 2012) describe quasi-neutral plasma, effects of finite ion gyroradius and the non-Maxwellian velocity distributions of ions. The ion drift-kinetic models (Whang, 1969; Whang and Ness, 1970; Catto, 1974; Lipatov, 1976, 2002; Lipatov et al., 2005) do not resolve the ion gyroradius and hence do not describe correctly the pickup ion dynamics. The electrostatic models (Farrell et al., 1998; Tao et al., 2012) also cannot be used for the pickup ion dynamics.

Hybrid models are suited to the modeling of the exospheric ions because they treat the ions kinetically. However, even hybrid models have limitations as they do not treat the wave-particle interactions on the electron scale. Also, the hybrid kinetic models do not include the charge separation which may be important at the lunar surface and the formation of the mini-magnetosphere. For those plasma processes we have to use full-kinetic codes (Deca et al., 2014; Usui et al., 2017; Saito et al., 2008). Nevertheless, the hybrid codes are sufficiently sophisticated to model the mass loading of the solar wind with pickup ions since the mass and the energy of the electrons play a secondary role in this process (see e.g. the mass loading in the cometary plasma (Bierman et al., 1967; Galeev and Lipatov, 1984; Schmidt and Wegmann, 1981)).

Effects of the orientation of the interplanetary magnetic field were previously studied in the absence of pickup ions. The 2.5-D hybrid modeling by Travnicek et al. (2005) suggests that for given solar wind conditions, the downstream region of the lunar wake is dominated by electromagnetic turbulence with the frequencies near the local proton gyrofrequency for the cases with $\theta_{B,U} = 45^\circ$ and $\theta_{B,U} = 90^\circ$ due to the proton temperature anisotropy. Here $\theta_{B,U}$ denotes the angle between the interplanetary magnetic field and the solar wind bulk velocity. Note that this result was produced with a fine spatial mesh and an assumption that the lunar radius is about a few ion inertial lengths. 3-D hybrid simulations produced by Holmström et al. (2012) and Fatemi et al. (2013) show symmetrical perturbation of the magnetic field in case with $\theta_{B,U} = 0^\circ$ and no strong asymmetry of magnetic field profile in the central plane across the magnetic field in case with $\theta_{B,U} = 90^\circ$.

The effects of lunar ions on the Moon-solar wind interaction have not been seriously considered. It is frequently assumed that no mass loading occurs, that lunar ion trajectories can be modeled as if the solar wind field does not bend down to the lunar surface (Sarantos et al., 2012b; Halekas et al., 2011), and that protons reflected by lunar crustal magnetic fields are one of the main factors shaping the global lunar plasma environment (see e.g. hybrid modeling by Fatemi et al. (2014, 2015), Halekas et al. (2017)). Although we do not consider here the effect of reflected protons, we explore in more details than all previous works the effect which planetary ions have on shaping the lunar environment. In our previous paper (Lipatov et al., 2013b) we used Na^+ as the main heavy lunar ion constituent, and considered its influence on the global interaction along with lighter species (H^+, H_2^+, and He^+). However, both calculations (Sarantos et al., 2012b) and observations anticipated that Na would not be the most important heavy ion species.

Considering only the Na^+ species would underestimate the total contribution of the lunar exo-ionosphere. Thus heavy lunar ions are hereby modeled with the same mass as Na but with about ten times higher production rate. This approximation is more practical than using numerous other species in this hybrid simulation considering that no single dominant species can describe the total effect of the lunar exosphere. Rather, numerous species (Al^+, CO^+, Ar^+, and molecular ions at high latitudes) contribute with approximately equal rates (Mall et al., 1998; Poppe et al., 2016; Choudhary et al., 2016). Note here that the estimation of the electron production rate is based on quasi-neutrality condition in the hybrid model. The use of the same mass ratio for heavy pickup ions and Na^+ is a simplification; however, this approximation is not expected to significantly affect the lighter mass pickup ion structures. The modeling with a set of higher mass pickup ions will be considered in future publications.

In the current paper we applied $\theta_{B,U} = 90^\circ$ orientation of the incoming magnetic field to a model of the neutral exosphere with H or H_2, He and Na species. We chose various production rates for the neutral exosphere to study the phase-mixing of the ion species. We used a code which combines a Boltzmann particle-in-cell approach (Lipatov et al., 1998), together with a hybrid plasma model (Lipatov, 2002) in three spatial and velocity dimensions (see, e.g., Lipatov and Combi (2006)). Charge exchange between upstream and pickup ions and the exospheric neutrals were also included.

2. Hybrid model description

2.1. Formulation of the problem

A quasi-neutral hybrid model is used that employs a kinetic description of the upstream and implanted pickup ions, and a fluid description of electrons, to study the interaction between the solar wind and the ionized and neutral components of the lunar environment (Lipatov, 2002; Lipatov et al., 2012a, 2013b). This model describes well the wave-particle interactions on the ion spatial and time scales ($\rho_{ci} = U_0/\Omega_i$ and $\omega \le \Omega_i$), where ρ_{ci} is the gyroradius for ions. U_0 and Ω_i denote the upstream velocity and the ion gyrofrequency. Our model takes into account ionization and charge exchange.

In our modeling coordinate system, the X axis is directed away from the Sun, Y axis is oriented in the direction of Earth's orbit, and Z axis completes the right-handed system. Note that the position of the center of the Moon is $x = 0, y = 0, z = 0$.

Mass and charge state of the ions under consideration are the following: solar wind protons - $M_1 = M_{H^+}$; in Sect. 3.2.2 (light pickup ions with lower production rate) $M_2 = M_{H^+}$ (ions from the lunar hydrogen corona) whereas in Sect. 3.2.1 (light pickup ions with higher production rate) $M_2 = M_{H_2^+}$ (ions from the H_2^+ exosphere); heaver pickup ions - $M_3 = M_{He^+}$, $M_4 = M_{Na^+}$. All these ions of mass M_s for $s = 1 - 4$ are