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# Effects of $Na^+$ and $He^+$ pickup ions on the lunar-like plasma environment: 3D hybrid modeling

A.S. Lipatov<sup>a,\*</sup>, J.F. Cooper<sup>b</sup>, E.C. Sittler Jr.<sup>b</sup>, R.E. Hartle<sup>b</sup>

<sup>a</sup> *GPHI UMBC/NASA GSFC, Code 673, Greenbelt, MD 20771, USA*

<sup>b</sup> *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

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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 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  $Na^+$  and  $He^+$  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.  
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**Keywords:** Exospheres; Pickup ions; Induced magnetospheres; Satellites; Pickup ions; 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:  $n_{Na} = 17\text{--}70\text{ cm}^{-3}$ ,  $n_{He} = 336\text{--}2000\text{ cm}^{-3}$ ,  $n_O = 321\text{--}500\text{ cm}^{-3}$ ,  $n_H = 65\text{--}17\text{ cm}^{-3}$ , and  $n_{H_2} = 7.6\text{--}9000\text{ cm}^{-3}$ . 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., 2011).

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; Wiehle et al., 2011; Holmström et al., 2012; Wang et al., 2011), drift kinetic (Whang, 1969; Whang and Ness, 1970; Catto,

\* Corresponding author. Tel.: +1 3012860906; fax: +1 3012861648.

E-mail addresses: [Alexander.Lipatov-1@nasa.gov](mailto:Alexander.Lipatov-1@nasa.gov) (A.S. Lipatov), [John.F.Cooper@nasa.gov](mailto:John.F.Cooper@nasa.gov) (J.F. Cooper), [Edward.C.Sittler@nasa.gov](mailto:Edward.C.Sittler@nasa.gov) (E.C. Sittler Jr.), [Richard.E.Hartle@nasa.gov](mailto:Richard.E.Hartle@nasa.gov) (R.E. Hartle).

1974; Lipatov, 1976; Lipatov, 2002; Lipatov et al., 2005), and electrostatic (Farrell et al., 1998; Tao et al., 2012) 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 field 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), Wiehle et al. (2011) 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 (*Na, He*) are chosen from Hartle and Killen (2006). Note, that we already performed the modeling the dynamics of  $O^+$  pickup ions near the Moon (Lipatov et al., 2011). 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., 2002) 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 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 ( $\lambda$ ) and time ( $\omega^{-1}$ ) scales:  $\lambda \sim \rho_{ci} = U_0/\Omega_i$  or  $\lambda \sim c/\omega_{pi}$  and  $\lambda \gg \rho_{ce}$ ;  $\omega \leq \Omega_i$ , where  $\rho_{ci}$  and  $\rho_{ce}$  denote the gyroradii for ions and electrons (respectively);  $U_0$  is the bulk velocity of the background plasma;  $c/\omega_{pi}$  denotes the ion inertial length, and  $\Omega_i$  is the ion gyrofrequency. The length  $\lambda$  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. The exosphere is considered to be an immobile component in this paper.

The general scheme of the global interaction of the solar wind with the Moon and the ARTEMIS trajectory is given

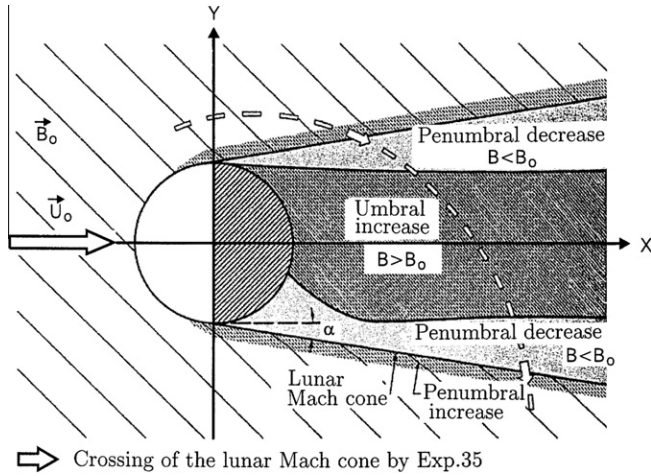


Fig. 1. Lunar plasma environment and the system of coordinates.

in Fig. 1. The ARTEMIS flybys always occurred behind the Moon. The orbit does not directly cross the center of the wake. In our coordinate system the  $X$  axis is directed away from the Sun,  $Y$  is directed in the direction of Earth's orbit, and  $Z$  axis completes the right-handed system.

In the hybrid model described here, the dynamics of upstream ions and implanted ions use a kinetic approach, while the dynamics of the electrons is described by a hydrodynamical approximation. We use a standard 3D hybrid code (see e.g. Lipatov et al., 2011; Lipatov, 2002 for details). Here we assume that the mass and charge state of the ions are  $M_s$  and  $Z_s = 1$ . The subscript  $s$  denotes the ion population:  $s = 1$  for  $H^+$  upstream ions and  $s = 2, 3$  for  $Na^+$  and  $He^+$  pickup ions. We also take into account the interaction of ions with neutral particles by charge exchange (see Eqs. (12–15) from Lipatov and Combi, 2006), and we assume that the bulk velocity and thermal temperatures of neutral particles equal zero.

We further assume quasi-neutrality

$$n_e = \sum_{s=1}^{N_{\text{species}}} n_s. \quad (1)$$

For massless electrons the equation of motion of the electron fluid takes the form of standard generalized Ohm's law (e.g. Braginskii, 1965):

$$\mathbf{E} = \frac{\mathbf{J}_e \times \mathbf{B}}{en_e c} - \frac{\nabla p_e}{en_e}, \quad (2)$$

where  $p_e = nm_e \langle v_e'^2 \rangle / 3 = n_e T_e$  is the scalar electron pressure, and  $v_e'$  is the thermal velocity of electrons;  $J_e$  denotes the electron current.

Since we suppose that electron heating due to collisions with ions is very small, the electron fluid is considered adiabatic. For simplicity we assume that the total electron pressure may be represented as a sum of partial pressures of all electron populations:

$$p_e \propto \frac{(\beta_e n_{i,\text{up}}^{5/3} + \sum_s \beta_{e,\text{PI},s} n_{i,\text{PI},s}^{5/3})}{\beta_e}, \quad (3)$$

where  $\beta_e$  and  $\beta_{e,\text{PI},s}$  denote electron beta for the upstream and pickup populations, respectively. We also assume here that  $n_{e,\text{up}} = n_{i,\text{up}}$ , and  $n_{e,\text{PI},s} = n_{i,\text{PI},s}$ . Here,  $n_{i,\text{iono}}$  denotes the immobile heavy pickup ion cloud. Otherwise, we have to calculate the electron pressure from heat balance for electrons (see, e.g. Braginskii, 1965) taking into account the heat fluxes for pickup electrons and exospheric electrons on the right side of this equation. The ion kinetic approach allows us to take into account the effects of anisotropy of ion pressure, the correct mass loading processes, the penetration of ions across the exosphere, and the asymmetry of plasma flow around the Moon. Recall that the fluid models, which account only for the scalar (i.e., isotropic) ion pressure, may result in an extra-expansion of the pickup ions along the magnetic field. Our computational model may also include charge exchange between magnetospheric ions and exospheric atoms, and between heavy pickup ions and exospheric atoms (see, e.g. Lipatov and Combi, 2006).

The neutral exosphere of the Moon serves as a source of new ions, mainly by electron stimulated desorption (McLain et al., 2011) and also by photoionization. The neutral exosphere also serves as collisional targets for charge exchange with the upstream flow  $H^+$  ions. The impacting ions consist both of upstream flow ions as well as newly implanted ions which are picked up by the motional electric field.

We have adopted a two-species description for the neutral exosphere of the (Hartle et al., 2011) exponentials form

$$n_{\text{neutral},k} = \Psi(\theta, \phi) n_{\text{exo},k} \exp(-(r - r_{\text{exobase}})/h_{\text{exo},k}). \quad (4)$$

Eq. (4) represents a numerical approximation of the exosphere model for the Moon. The function  $\Psi \propto \cos^2 \theta$  has a maximum value in the direction toward the Sun, and it has a zero value at the night-side. In Eq. (4),  $n_{\text{exo},k}$  is the maximum value of the neutral density extrapolated to the exobase, and  $r_{\text{exobase}} \approx R_M$ . Index  $k$  denotes  $He$ , and  $Na$ . Here the maximum value of the neutral density at the exobase are  $n_{\text{exo},He} = 2.0 \times 10^3 \text{ cm}^{-3}$  and  $n_{\text{exo},Na} = 1.0 \times 10^2 \text{ cm}^{-3}$  (Wang et al., 2011). Note that these values are much less than the experimental total exospheric density of considerably larger scale height of atoms released via sputtering into the exosphere (Wurz et al., 2007). The model developed in Hartle and Thomas (1974) gives the following range for the maximum value of  $He$  density:  $2 \times 10^3 \text{ cm}^{-3} < n_{\text{exo},He} < 4 \times 10^4 \text{ cm}^{-3}$ . We now study the models with much low value of the neutral density at the exobase. The spatial scales are  $h_{\text{exo},He} = 498 \text{ km}$  and  $h_{\text{exo},Na} = 87 \text{ km}$  (Hartle and Killen, 2006). The thermal velocity of all newly formed pickup ions is about 2.0 km/s.

The production of new ions from the exosphere near the Moon corresponds to

$$G_{\text{exo},k} = \Psi(\theta, \phi) v_{i,k} n_{\text{exo},k} \exp[(r - r_{\text{exobase}})/h_{\text{exo},k}]. \quad (5)$$

Here  $n_{\text{exo},k}$  denotes the value of the neutral component density at  $r = r_{\text{exobase}}$  and  $v_{i,k}$  is the effective ionization rate per atom or molecule of species  $k$ . The effective value of the ionization are  $v_{i,He} = 7.8 \times 10^{-9} \text{ s}^{-1}$  (Wang et al., 2011)



and  $v_{i,Na} = 1.8 \times 10^{-5} \text{ s}^{-1}$  (Potter and Morgan, 1988; Wang et al., 2011; Gruntman, 1996). The total pickup ion production rates are  $Q_{He^+} \approx 1.0 \times 10^{21} \text{ s}^{-1}$  and  $Q_{Na^+} \approx 2.0 \times 10^{22} \text{ s}^{-1}$ . The physical processes near the moon are described by total pickup ion production rates rather than by local values of the pickup ion production rates. The generation of pickup ions was produced with a variable weight of the macro-particles (see, e.g. Lipatov, 2012).

### 2.1. Initial conditions

Initially the computational domain contains only super-Alfvénic and supersonic solar wind flow with a homogeneous spatial distribution and a Maxwellian velocity distribution; the pickup ions have a weak density and spherical spatial distribution. The magnetic field and electric fields are  $\mathbf{B} = \mathbf{B}_0$  and  $\mathbf{E} = -\mathbf{U}_0 \times \mathbf{B}_0/c$ . Inside the Moon the electromagnetic fields are  $\mathbf{E} = 0$  and  $\mathbf{B} = \mathbf{B}_0$ , and the bulk velocities of ions and electrons also equal to zero.

At  $t > 0$  we begin to inject the pickup ions with a distribution according to Eq. (5). Far upstream ( $x = -5L$ , where  $L = R_M$ ), the ion flux is assumed to have a Maxwellian distribution,

$$f = n_\infty (\pi v_{th}^2)^{-3/2} \exp \left[ -\frac{(\mathbf{v} - \mathbf{U})^2}{2v_{th}^2} \right], \quad (6)$$

where  $v_{th}$  and  $\mathbf{U}$  are the thermal and the bulk velocities of the background plasma flow, respectively.

### 2.2. Boundary conditions

At the side boundaries we use a damping boundary condition for the electromagnetic field. At the back boundary we use a “Sommerfeld” radiation condition for the magnetic field, and a free escape condition for particles, with re-entry of a portion of the particles from the outflow plasma. The magnetic field and electric fields are  $\mathbf{B} = \mathbf{B}_0$  and  $\mathbf{E} = -\mathbf{U}_0 \times \mathbf{B}_0/c$ .

Inside the Moon, the bulk velocities of ions and electrons also equal to zero.

We also take into account the effect of the finite conductivity of the lunar body so that

$$\begin{aligned} R_{m,eff} &= R_{m,shell}, & \text{for } R_M > r > R_{core}, \\ R_{m,eff} &= R_{m,core}, & \text{for } r \leq R_{core}, \end{aligned} \quad (7)$$

where  $R_{m,shell}$  and  $R_{m,core}$  denote the effective magnetic Reynolds numbers ( $R_m = 4\pi U_0 L \sigma_{eff}/c^2$ ) in the weak-conducting shell and conducting core, the values of which are presented in Sect. “Results of Modeling”.  $R_{core}$  is the radius of the lunar core. Note, that of Cartesian mesh can provide a solution of the Maxwell equations only in the first approximation. The more precise solution inside the lunar interior one has to use the spherical system of coordinates (see, e.g. Lipatov, 1976).

Far downstream, we adopted a free escape condition for particles and Sommerfeld’s radiation condition for the magnetic field. On the side boundaries ( $y = \pm DY/2$  and  $z = \pm DZ/2$ ), periodic boundary conditions were imposed for incoming flow particles and the electromagnetic field. The pickup ions exit the computational domain when they intersect the surfaces  $y = \pm(DY/2 - 5 \times \Delta y)$ , or  $z = \pm(DZ/2 - 5 \times \Delta z)$ , or  $x = 20L - 5 \times \Delta x$ . Thus there is no influx of pickup ions at the side boundaries. At the Lunar surface,  $r = R_M$ , the particles are absorbed. There is no boundary condition for the electromagnetic field, and we also use our equations for the electromagnetic field inside the Moon, but with internal conductivity and the bulk velocity that is calculated from the particles. In this way the jump in the electric field is due to the variation of the value of the conductivity and bulk velocity across the lunar surface. Note that the position of the center of the Moon is  $x = 0$ ,  $y = 0$ ,  $z = 0$ .

The three-dimensional computational domain has dimensions  $DX = 25L$ ,  $DY = 40L$ , and  $DZ = 20L$ , where  $L = R_M = 1738 \text{ km}$ . We used meshes of  $251 \times 401 \times 201$  grid points, and  $6 \times 10^8$  and  $8 \times 10^7$  macro-particles for protons and pickup ions, respectively, for a homogeneous mesh computation. The time step  $\Delta t$  satisfies the condition  $v_{max} \Delta t \leq \min(\Delta x, \Delta y, \Delta z)/16$ .

The relationship between dimensional ( $U, E, B, p_e, n, T$ ) and dimensionless ( $U', E', B', p'_e, n', T'$ ) parameters may be expressed via the dimensional upstream values as follows:

$$\begin{aligned} \mathbf{U} &= \mathbf{U}' U_0, & \mathbf{E} &= \mathbf{E}' B_0 U_0/c, & \mathbf{B} &= \mathbf{B}' B_0, & p_e &= p_e' p_{e0}, \\ n &= n' n_0, & T &= T' M_i U_0^2, \end{aligned} \quad (8)$$

whereas the dimensional time and distance may be expressed via the bulk velocity  $U_0$  and characteristic scale  $L = R_M$ :

$$t = t' L/U_0, \quad \mathbf{x} = \mathbf{x}' L. \quad (9)$$

The global physics in the lunar environment is controlled by a set of dimensionless independent parameters such as  $M_A$ ,  $\beta_i$ ,  $\beta_e$ ,  $M_{PI}/M_p$ , ion production and charge exchange rates, diffusion lengths, and the ion gyroradius  $\rho_{ci}$ . For real values of the magnetic field the value of the  $H^+$  upstream ion,  $He^+$  and  $Na^+$  pickup ion gyroradii are about 250 km, 1000 km and 5700 km (respectively) which are calculated from the local bulk velocity. The grid spacing has the value  $\Delta_x = 175 \text{ km}$ .

In order to study ion kinetic effects (e.g. excitation of low-frequency oscillations ( $\omega \ll \Omega_b$ ) by the mass loading), we must satisfy the condition  $\Delta \leq (10 - 20)c/\omega_{pb}$ , where  $\Omega_b$  and  $\omega_{pb}$  denote the gyrofrequency and the plasma frequency for background ions (Winske et al., 1985). The above estimation of the plasma parameters shows that we have good resolution for the low-frequency waves. To excite high-frequency waves ( $\Omega_b \ll \omega \ll \Omega_e$ ) we must satisfy the condition  $\Delta \leq 0.25c/\omega_{pb}$ , (Winske et al., 1985) for background ions. The above estimation shows that

we have insufficient resolution for the high-frequency waves.

### 3. Results of the modeling

To study the interaction of the solar wind with the heavy ion cloud near the Moon the following sets of the magnetospheric plasma and exosphere parameters were adopted in accordance with flyby observational data: upstream velocity, densities and magnetic field:  $U_0 = 305$  km/s;  $\mathbf{U}/U_0 = (1., 0., 0.)$ ;  $n_0 = n_{H^+} = 3.0$  cm $^{-3}$ ;  $B_0 = 5.2$  nT;  $\mathbf{B} = (-1., 1.0, 5.0)$  nT;  $M_A = 5.17$ ;  $M_S = 3.66$ ;  $\beta_{H^+} = 0.2$ ;  $\beta_e = 0.5$  and  $\beta_{pickup,e} = 0.05$ . The effective Reynolds numbers inside the shell and core of the Moon are  $R_{m,shell} = 0.05$  and  $R_{m,core} = 0.2$ . The radius of the lunar core  $R_{core}$  equals  $0.5 R_M$ .

In this section we discuss the results of a modeling at time  $t = 5T_{transit}$ , where  $T_{transit}$  denotes an average transition time for particle from the left (upstream) boundary to the right (downstream) boundary.

#### 3.1. Global structure of the lunar environment

Fig. 2 demonstrates 2-D cuts of the upstream ion density (top),  $Na^+$  pickup ion density (middle), and  $He^+$  pickup ion density (bottom). The  $x$ – $y$  cuts (left column) are located at  $z/L = 0$ ,  $y$ – $z$  cuts (middle column) are located at  $x/L = 2.4$ , and  $x$ – $z$  cuts (right column) are located at  $y/L = 0$ . The modeling shows the formation of the asymmetric Mach cone (for  $y < 0$ , Fig. 2, top) in the solar wind due to mass loading by the heavy pickup ions (for  $y > 0$ , Fig. 2, middle and bottom). The modeling also demonstrates three peaks in the background ion density profile across the Mach cone transition ( $N_2/n_0 \approx 2.2; 1.7; 1.4$ ) for  $x = 2.4 L$  and  $z = 0$ . The average value of the proton density inside the Mach cone is about  $1.2 n_0$ . The ARTEMIS observations (see Figs. 4 and 5 from Halekas et al., (2011); Wiehle et al., 2011) also show three peaks in the density profile ( $N_2/n_0 \approx 1.4; 1.3; 1.1$ ) for the time interval  $09.40 \leq t \leq 09.50$  ( $2.2 < x/L < 2.6$ ,  $0 < y/L < -0.3$ , and  $1.4 < z/L < 1.7$ ). However, these peaks are wider and

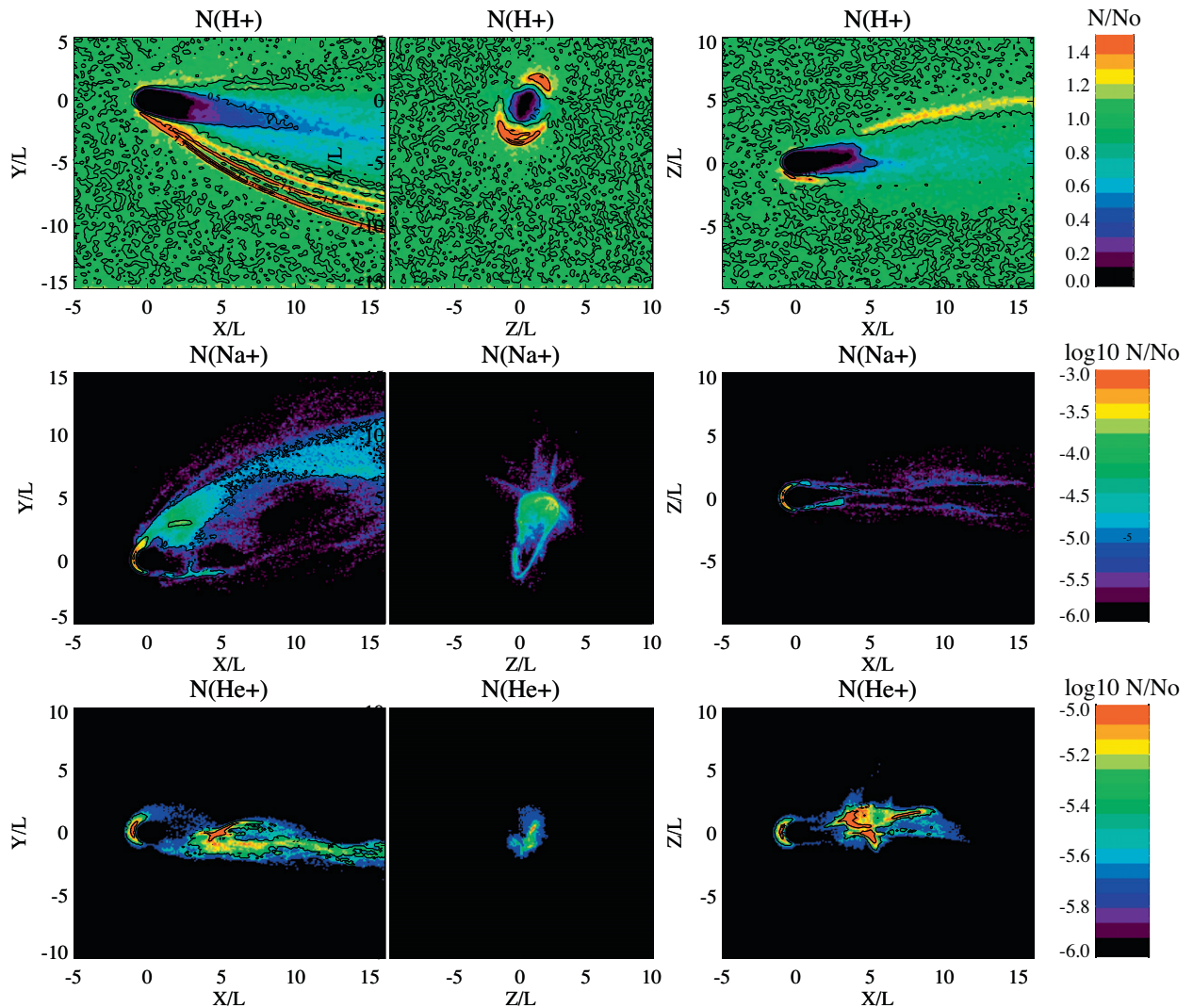


Fig. 2. 2-D cuts of the upstream  $H^+$  ion (top), and  $Na^+$ ,  $He^+$  pickup ion (middle and bottom) density profile. Here  $No = n_{H^+} = 3.0$  cm $^{-3}$ .  $x$ – $y$  cuts (left column) are located at  $z/L = 0$ ,  $y$ – $z$  cuts (middle column) are located at  $x/L = 2.4$ , and  $x$ – $z$  cuts (right column) are located at  $y/L = 0$ .

weaker than it was observed in our modeling. Such disagreement may be explained by the overestimated conductivity of the lunar interior model or by the possible dissipation processes. The central region of the plasma wake is oblique to the solar wind bulk velocity.

The modeling gives the following maximum values of the background and pickup ion density near the exobase:  $n_{H^+}^{max} = 1.1 n_0$ ,  $n_{Na^+}^{max} = 9 \times 10^{-4} n_0$ ,  $n_{He^+}^{max} = 1.2 \times 10^{-5} n_0$ , where  $n_0 = 3.0 \text{ cm}^{-3}$ . The  $Na^+$  heavy pickup ions form a complex two-tail structure – external and internal tails. The external tail is formed by the pickup ions created near the lunar surface with  $y > 0$ . The internal tail is formed by the pickup ions created on the other side of the lunar surface. The splitting the pickup ion environment into a two-tail structure may be explained by the acceleration of pickup ions due to the polarization electric field. Near the exobase, the radial electric field is mainly determined by the electron pressure and it is oriented out of exobase.

The splitting the pickup ion tail was also observed in the modeling of the solar wind-weak comet interaction (see, e.g. Lipatov et al., 1997; Lipatov, 2002). The trajectory of the heavy  $Na^+$  pickup ions in the outer tail is similar to a test particle motion with an average value of the gyroradius about of  $3 \times 10^4 \text{ km}$ . The heavy  $He^+$  pickup ions also create two-tail structure. The ions in outer tail move along the cycloid with average gyroradius about of  $5 \times 10^3 \text{ km}$ . The internal tail has a quasi-straight form with perturbations along the tail. A small portion of the  $He^+$  pickup ions move along the cycloid just between the external and internal tails.

Fig. 3 shows the 2-D cuts of the  $B_x$  (top),  $B_y$  (middle) and  $B_z$  (bottom) magnetic field profiles. Here, the  $x$ – $y$  cuts (left column) are located at  $z/L = 0$ ,  $y$ – $z$  cuts (middle column) are located at  $x/L = 2.4$ , and  $x$ – $z$  cuts (right column) are located at  $y/L = 0$ . Fig. 3 (left and right columns, bottom) also confirms a formation of the asymmetrical Mach cone.

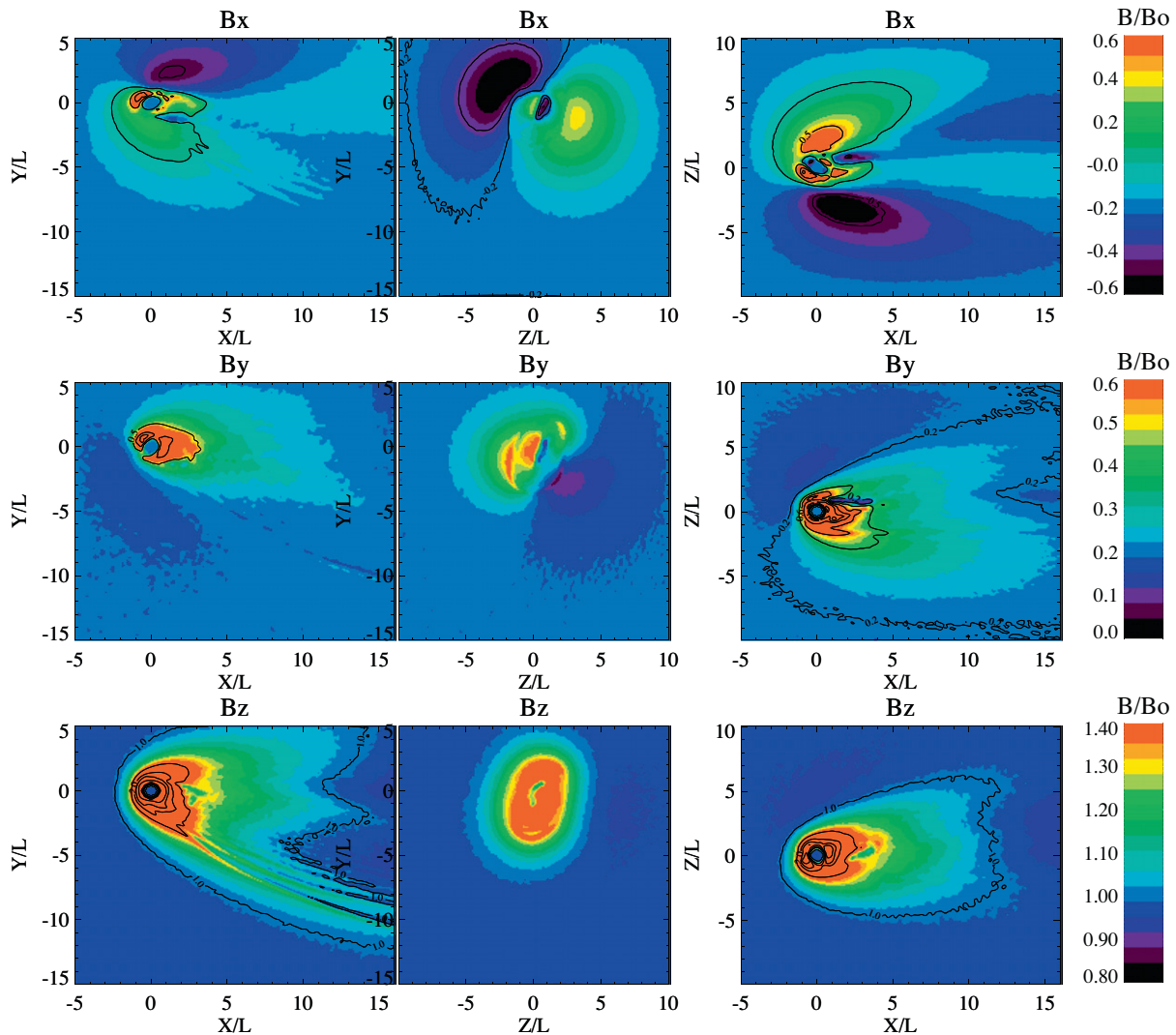


Fig. 3. 2-D cuts of the  $B_x$  (top),  $B_y$  (middle) and  $B_z$  (bottom) magnetic field profile.  $x$ – $y$  cuts (left column) are located at  $z/L = 0$ ,  $y$ – $z$  cuts (middle column) are located at  $x/L = 2.4$ , and  $x$ – $z$  cuts (right column) are located at  $y/L = 0$ .



As one may see that magnetic field topology follows the upstream  $H^+$  profile for  $y < 0$  (asymmetric Mach cone) and weak perturbation in the region of the heavy  $Na^+$  pickup ion mass loading, Fig. 3 (middle and bottom). The value of the magnetic field in the lobe side of the magnetic barrier is about  $3.5B_0$ . The average jump in the magnetic field at the front of the Mach cone is about  $B_2/B_0 \approx 1.5$ .

The results of the measurements by the particles and field instruments on the ARTEMIS P1 spacecraft provided new and important information with which realistic model for the plasma interaction can be tested. However, it still needs to be compared the modeling results with observational data in the case when the orbit of satellite is oriented perpendicular to the upstream magnetic field. The recent observations (Wang et al., 2011) indicate the existence of the exospheric  $H_2^+$  ( $m/q = 2$ ) pickup ions. The measurements on board the KAGUYA spacecraft (Tanaka et al., 2009) also observed the Moon-origination ions in the Earth's magnetosphere, so that pickup ion dynamics become a very important task for interpretation of the recent in-situ investigations of the lunar plasma environment. The results of the modeling of light pickup ions will be discussed in future publications.

Here we have discussed only one model for the lunar exosphere and heavy ion cloud. We should also note that the hybrid model for ARTEMIS with heavy ion cloud produces another picture of the plasma-Moon interaction due to of solar wind mass loading by the heavy pickup ions.

In the outer region of the exosphere the velocity distributions of the  $Na^+$ ,  $He^+$  pickup ions must be ring-like distributions. The ring-type of the velocity distribution for  $Na^+$ ,  $He^+$  pickup ions observed in modeling could cause generation of ion cyclotron waves in the far plasma wake. Future modeling possibly will demonstrate the generation of these waves in the distant plasma wake.

One may also see strong phase mixing in the plasma wake. The plasma wake demonstrates the formation of time-dependent structuring in the pickup ion tails and the splitting of the pickup ion tails. Such finite gyroradius effects were also observed in 2.5 D hybrid and bi-fluid modeling of a weak comet and Pluto (see, e.g. Lipatov, 2002; Lipatov et al., 1997; Sauer et al., 1996, 1997).

Our hybrid modeling shows that the existence of pickup ions near the surface of the Moon may change the global picture of interaction between the solar wind and the Moon due to finite gyroradius effects in compare with the previous studies without the pickup ions (see e.g. Farrell et al., 1998; Birch and Chapman, 2001; Travnicek et al., 2005; Kallio, 2005; Lipatov et al., 2005; Holmström et al., 2012; Wiehle et al., 2011; Wang et al., 2011). The formation of the asymmetrical Mach cone due to mass loading by pickup ions was also observed in the 2.5 D bi-fluid and 2.5 D/3D modeling of the weak comet and Pluto (see, e.g. Lipatov, 2002; Lipatov et al., 1997; Sauer et al., 1996, 1997). In Omid and Winske, 1990, numerical simulations are used to investigate the nonlinear evolution

of oblique low-frequency electromagnetic (kinetic magnetosonic) waves, which have been observed upstream of planetary bow shocks and at comet Giacobini–Zinner. These waves have been referred to as shocklets. So, we can expect that the splitting of the Mach cone which was observed in our hybrid modeling may be connected with a formation of these shocklets.

#### 4. Conclusions

The hybrid modeling of Lunar plasma environment with ARTEMIS parameters with 3 ion species demonstrated several features:

- The light ( $He^+$ ) and heavy ( $Na^+$ ) pickup ions form a multiple structured wake with external and internal tails.
- The pickup ions form a conducting layer near the day-side lunar surface and cause a compression in the magnetic field on the day-side of the lunar surface. The mass loading results in the formation of the asymmetrical Mach cone. The split structure of the Mach cone transition produces three peaks in the plasma density, magnetic and electric field distributions.
- The light and heavy pickup ions fill the lunar plasma wake, and, thus, alter the electromagnetic field dynamics in the lunar plasma wake.
- Our modeling may be important for the study of the interaction between the solar wind and very weak comets, Mercury, and Pluto.

Currently, we are modeling the heavy ( $Na^+$ ,  $He^+$ ) and light ( $H_2^+$ ,  $H^+$ ) pickup ions dynamics near the Moon. We are also modeling the effects of the magnetic anomalies. The result of this modeling will be discuss in future publications. It seems that Future modeling must resolve the multiscale effects near the lunar surface, in particular, to provide a realistic distribution of the conductivity inside the lunar interior. These models may include energetic background ions and electrons, and later fully kinetic model including electrons. Future modeling must use the composite grid structure, e.g. “Cubed sphere”, “Yin-Yang” grids (see, e.g. Koldoba et al., 2002; Kageyama and Sato, 2004 and references therein) to resolve the multiscale effects near the lunar surface and in the outer plasma environment. These approaches will allow us to delete the effects of the reflection of the waves on the side boundaries. This modeling will also allow us to study some kinetic wave-particle interaction effects in the plasma wake, such as the ion cyclotron waves that are expected to be observed in the distant plasma wake.

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