Lunar Plasma Environment in Magnetotail Lobe Conditions. First Results from 3-D Hybrid Kinetic Modeling and Comparison with ARTEMIS Observation

Alexander Lipatov[1], Jasper Halekas[2], Menelaos Sarantos[3], and John Cooper[4]

[1]University of Maryland Baltimore County
[2]University of Iowa
[3]NASA/GSFC
[4]NASA Goddard Space Flight Center (Emeritus)

November 22, 2022

Abstract

The study of lunar plasma environment's response to the magnetotail lobe condition is the main subject of our investigation in this report. Photoionization and charge exchange of protons with the lunar exosphere arethe ionization processes included in our model. The computational model includes the dynamics of heavy Na+ pickup and ambient magnetospheric ions. The electrons are considered as a fluid.The lunar interior is considered as a weakly conducting body. In this report we consider for the first time a formation of lunar plasma structures, wakes, and a generation of low-frequency electromagnetic waves by using a self-consistent hybrid kinetic modeling. The input parameters were taken from the ARTEMIS observations. At an early stage the Moon with exosphere and conducting core excites whistler waves in case of Sub-Alfvenic/sonic interaction. At a later stage an excitation of the Alfven wave is observed. The topology of the Alfven waves is approximately similar to the Alfven wing near the planetary moons (Io, Europa etc.). The physics of the Moon-magnetotail lobe interaction is also close to the physics of the interaction between plasma clouds (expanding and not expanding) and ambient magnetospheric plasma. The heavy pickup ions create a large structured halo with space scale of more than 10 R_{E} in the direction of the background field. The modeling also shows an excitation of the compressional waves due to expansion of heavy exospheric pickup ions. The lunar model with weaker interior conductivity excites lower levels of the wave activity. This work was supported by NASA Award (80NSSC20K0146) from Solar System Workings Program (NNH18ZDA001N-C.3-SSW2018). Computational resources were provided by the NASA High-End SupercomputingFacilities (Aitken-Ames, Project HEC SMD-20-02357875).

Lunar Plasma Environment in Magnetotail Lobe Conditions:

First Results from 3-D Hybrid Kinetic Modeling and Comparison with ARTEMIS Observations

Alexander S. Lipatov[a,c], Jasper S. Halekas[b], Menelaos Sarantos[c] and John F. Cooper[c]

[a] University of Maryland Baltimore County, Baltimore MD 21250

[b] University of Iowa, Iowa City, IA 52242

[c] NASA GSFC, Greenbelt, MD 20771

Fall 2021 AGU Meeting, 13–17 Dec. 2021, New Orleans, LA

2. Abstract-1

The study of lunar plasma environment's response to the magnetotail lobe condition is the main subject of our investigation in this report. 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 heavy Na^+ pickup ions. The electrons are considered as a fluid. The lunar interior is considered as a weakly conducting body. In this report we consider for the first time the formation of lunar plasma structures, wake, and a generation of low-frequency electromagnetic waves by using a selfconsitent hybrid kinetic modeling. The input parameters were taken from the ARTEMIS observations.

3. Abstract-2

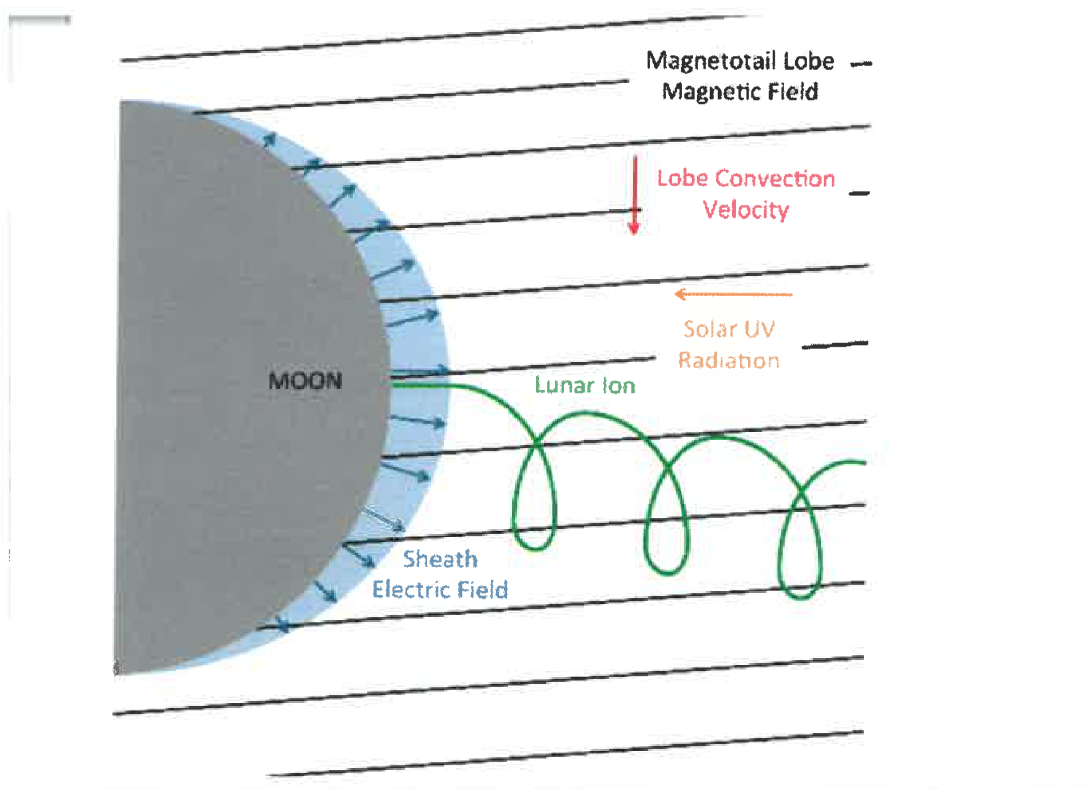
At an early stage the Moon with exosphere and conducting core excites whistler waves in case of Sub-Alfvenic/sonic interaction. At a later stage an excitation of the Alfven wave is observed. The topology of the Alfven waves is approximately similar to the Alfven wing near the planetary moons (Io, Europa etc.). The physics of the Moonmagnetotail lobe interaction is also close to the physics of the interaction between plasma clouds (expanding and not expanding) and ambient magnetospheric plasma. The heavy pickup ions create a large structured halo with space scale of more than $10R_E$ in the direction of the background field. The modeling also shows an excitation of the compressional waves due to expansion of heavy exospheric pickup ions. The lunar model with weaker interior conductivity excites lower levels of the wave activity.
This work was supported by NASA Award (80NSSC20K0146) from Solar System Workings Program (NNH18ZDA001N-C.3-SSW2018). Computational resources were provided by the NASA High-End Supercomputing Facilities (Aitken-Ames, Project HEC SMD-20-02357875).
References:
Lipatov, A.S., Halekas, J., Sarantos, M., Cooper, J.F., 2020. 80NSSC20K0146-SSW18-Progress-Report-2020, Sept. 2020.

Lipatov, A.S., Halekas, J., Sarantos, M., Cooper, J.F., 2021.

80NSSC20K0146-SSW18-Progress-Report-2021, Sept. 2021.

4. Motivation and Scheme of the Moon–magnetotail lobe interaction

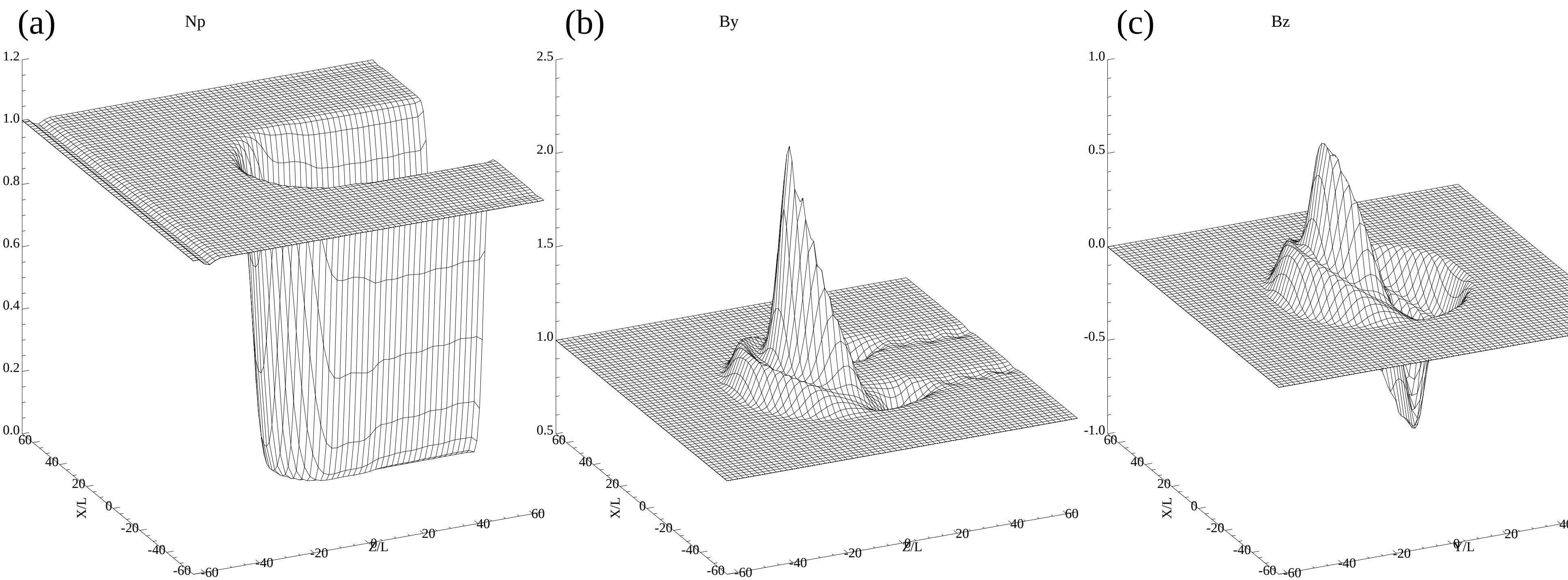
- 1. **Unique ARTEMIS observations of the solar wind parameters and the lunar plasma environment.**
- 2. **Plasma physics of pickup ions structures and plasma wake.**
- 3. **Particle acceleration and electromagnetic perturbations in the lunar plasma environment.**



5. Hybrid Model

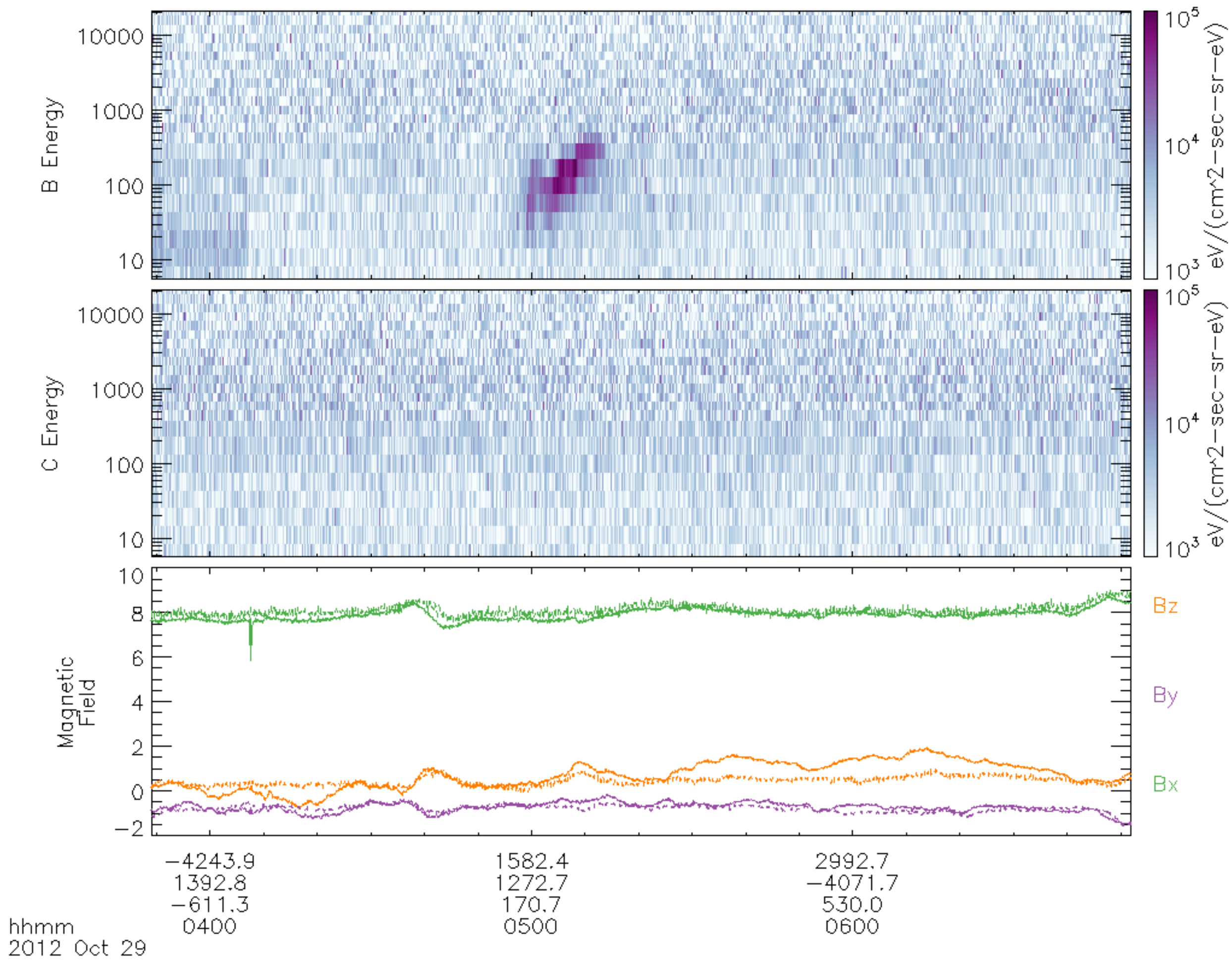
- *Kinetic - ions. Fluid - electrons*
- *Interpenetrating flows*
- *Effects of finite ion gyroradius estimated with thermal and bulk velocities:* $k_\perp \rho_{ci} \geq 1$, $k_\| \rho_{ci} \geq 1$ *and* $l \approx \rho_{ci}; \quad \omega \approx \Omega_{ci}$
- *The modeling tool: (a)* **Standard PIC** *[Harlow, 1957, LANL Report];* **ES - Shape Function Kinetics (SFK)** *[Larson & Young 2015] is a logical extension of* **Complex Particle Kinetics (CPK)** *[Hewett 2003; Lipatov 2012] and* **Finite Mass Method (FMM)** *[Yserentant et al. 1996-2007]*
- *The SFK and CPK* **aim to bridge the gap** *between continuum and kinetic methods. These methods may save a computational resources by factor more than* 100 *in compare with Standard PIC method*

6. Multi-Target EM-SFK Method. Individual Macro-Particle –> 6x6 Matrix



Example of an interaction between the Moon and the hypersonic solar wind (SW) from the modeling with a new 3-D hybrid kinetic EM-SFK method. The higher quality of the numerical solution was produced with only one macro-particle (location of the particle's center of mass plus deformation matrix) per cell distribution. The 3-D spatial grid had 64x64x64 cells and 5^6-point quadrature rules were used for time evolution of the Gaussian macro-particles in the 6-dimension phase space. Updated point particles were used to construct the new covariance matrices. A peak in the magnetic field was observed near conducting core. Here, z-axis is directed to the Sun, x-axis is oriented away to the direction of Earth's orbit, and x-axis completes the right-handed system. This modeling required 3GB RAM on laptop.

7. Moon in magnetotail lobe. Example of plots of the SW magnetic field, density, and velocity observed by ARTEMIS spacecraft.



8. 2-D cuts of density of the exospheric ions (a,d,g), ambient magnetospheric ions (b,e,h) and magnetic field (c,f,j)

Background parameters

$U_{0,x} = 20\,\text{km/s}$;

$B_0 = 5\,\text{nT}$;

$N_{H+,back} = 0.2\,cm^{-3}$;

$\beta_p = 0.0065$;

$\beta_e = 10.$ (a);

$\beta_e = 1.$ (d);

$\beta_e = 10.$ (g);

Pickup ions

$v_{th,Na} = 0.5\,\text{km/s}$ (a);

$v_{th,Na} = 0.1\,\text{km/s}$ (d);

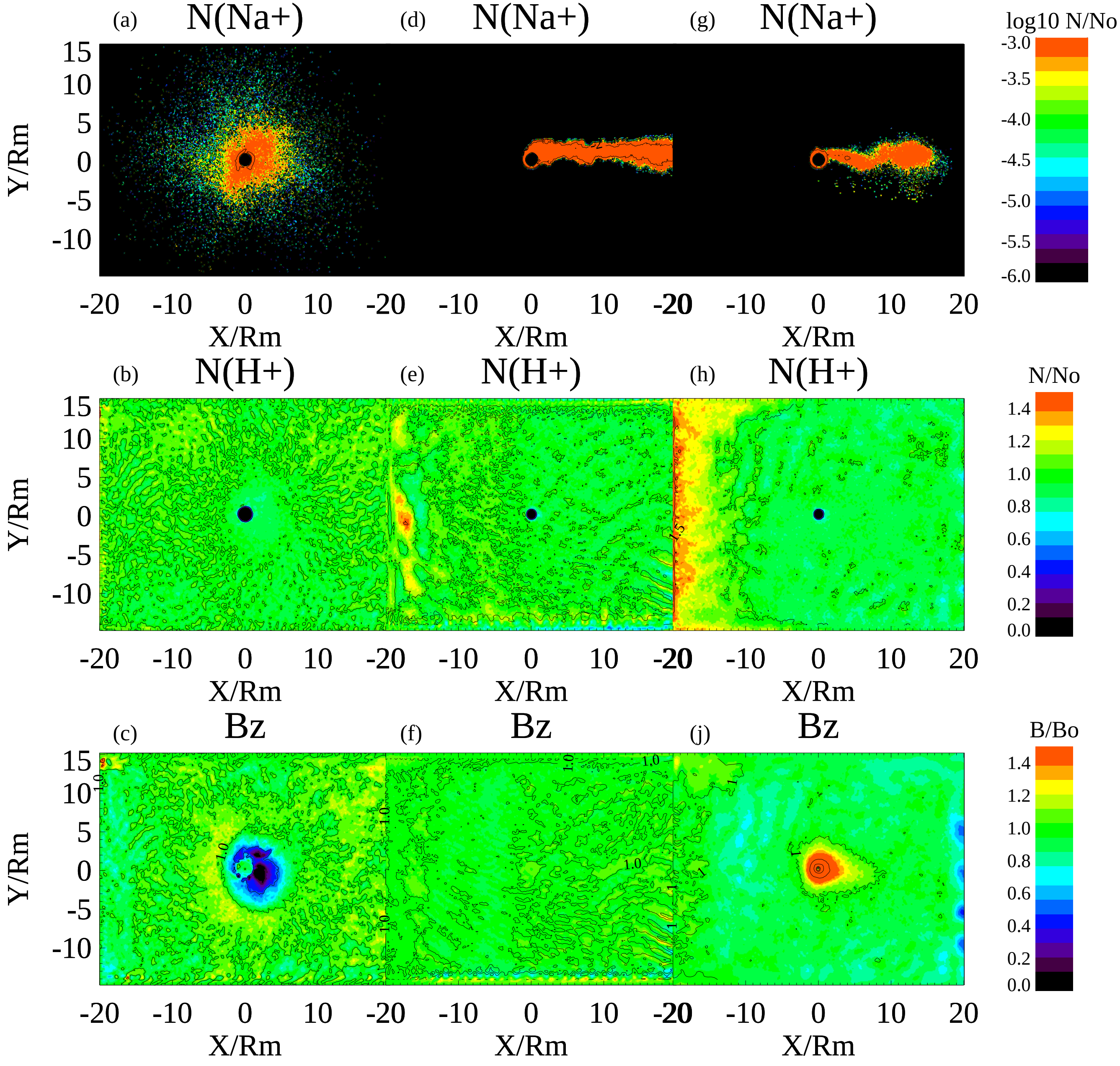
$v_{th,Na} = 0.1\,\text{km/s}$ (g);

Internal diffusion

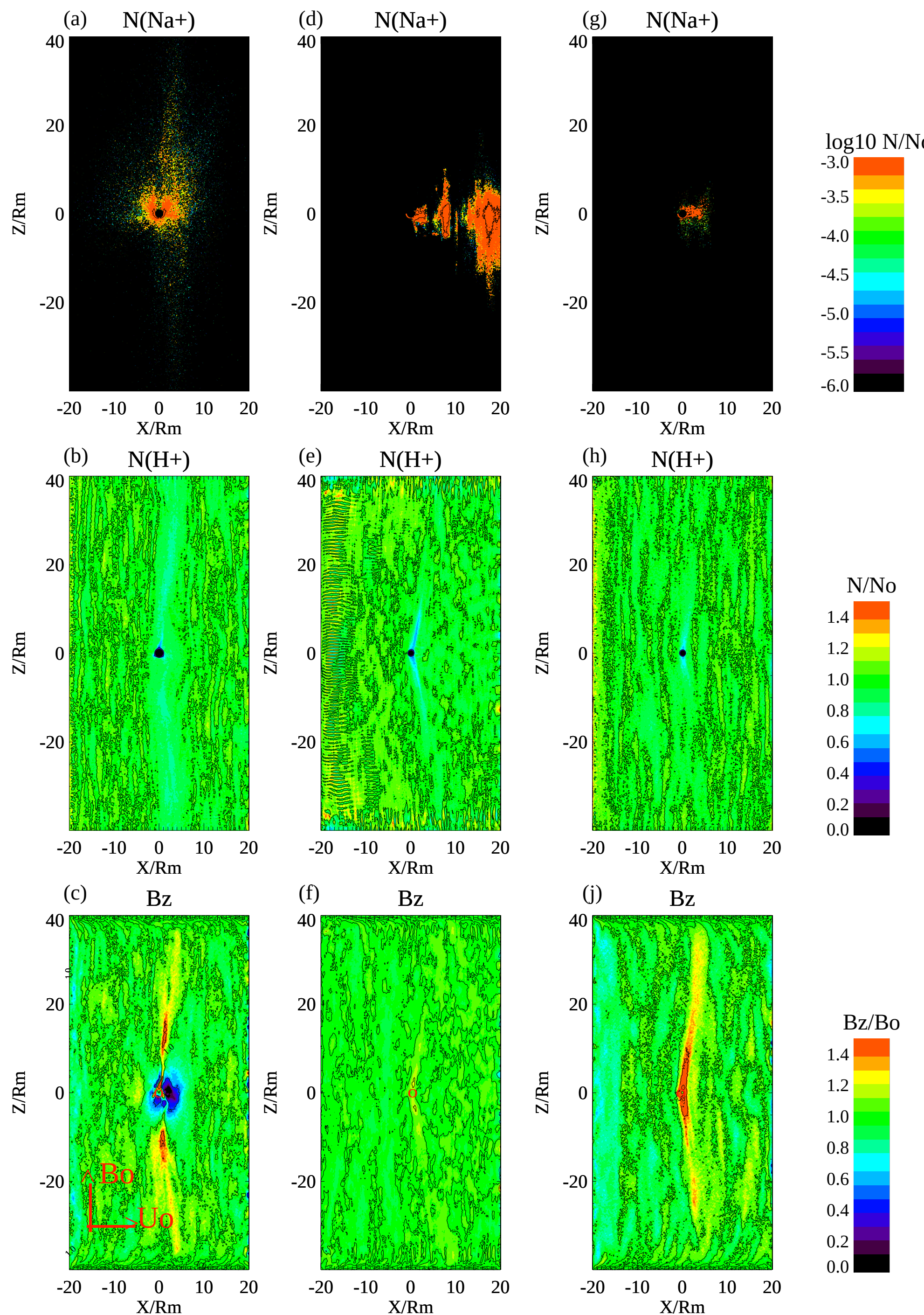
$l_d = 2.5$ (a);

$l_d = 0.025$ (d);

$l_d = 1.25$ (g);



9. 2-D cuts of density of the exospheric ions (a-g), ambient magnetospheric ions (b,e,h) and magnetic field (c,f,j)



10. SUMMARY

1. The lunar interior subsurface conductivity and conducting core, and initial velocity of the newborn exospheric ions play an important role in the shape formation of the exosphere.
2. In case of relatively high lunar internal conductivity the Moon forms a strongly expanding exosphere. The Moon excites whistler waves in the ambient magnetotail lobe plasma at an early stage. At a later stage an excitation of the Alfven wave is observed [4]. The topology of the Alfvenic waves is approximately similar the Alfven wing near the planetary moons (Io, Europa etc.).
3. The heavy pickup ions created a large structured halo with space scale of more than 10 R E the direction of the background field.
4. In case of lower lunar interior conductivity the shape and perturbations inside exosphere differs from the above case depending on the internal conductivity, conducting core and initial velocity of the exospheric ions.