One-dimensional particle-in-cell simulations of an ARTEMIS lunar wake crossing at 3.5 R_L

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Abstract

In February 2010, the ARTEMIS P1 spacecraft executed a lunar fly-by, passing through the lunar wake at approximately 3.5 lunar radii (R_L) downstream from the Moon. Detailed measurements were made of the plasma and electromagnetic field environment, including a density depletion in the wake, counter-streaming ion beams, and electrostatic wave activity. Additionally, the combination of a tilted interplanetary magnetic field orientation and an asymmetric solar wind electron distribution caused a resulting spatial asymmetry in the generation of electron beams and electrostatic waves [Halekas et al, SSR, 2011]. Here, we simulate the ARTEMIS P1 wake crossing with a one-dimensional, electrostatic particle-in-cell code in order to (1) reproduce the general characteristics of the lunar wake fly-by, (2) include the effect of the asymmetric nature of the interplanetary magnetic field and electron distribution, and (3) study the effect of these asymmetries on the generation of electron beams and electrostatic waves.

ARTEMIS P1 Fly-by

ARTEMIS Lunar Wake Fly-by, 2010

In February 2010, the ARTEMIS P1 spacecraft passed through the lunar wake at approximately 3.5 R_L downstream. In addition to characteristics consistent with those seen by WIND and later missions (LP, Chang'e, Kaguya), ARTEMIS P1 also observed asymmetric wake characteristics most likely due to the combination of a titled interplanetary magnetic field and an anisotropic solar wind electron distribution (the solar wind *strahl* population). **Figure 1** shows cuts of the ARTEMIS P1 trajectory above and below, **Figures 2** and **3** are the plasma and fields data for the fly-by.

Figure 1

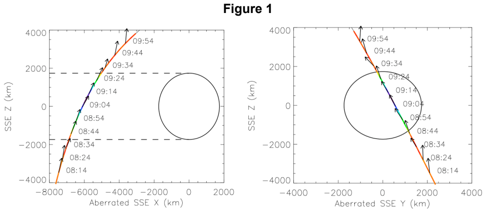


Figure 2

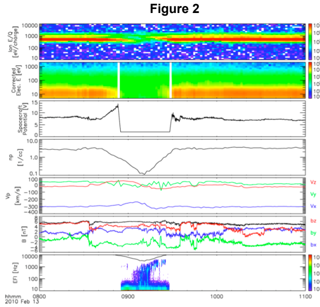


Figure 3

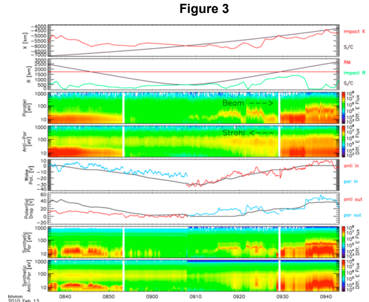
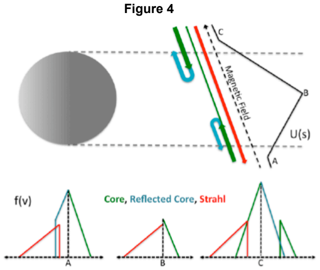


Figure 4

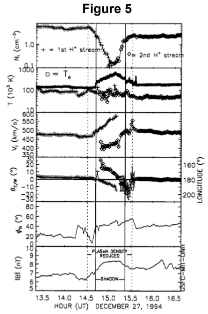


The Role of Anisotropic Electron Distributions

At the time of the ARTEMIS P1 fly-by, the interplanetary magnetic field was angled with respect to the downstream axis. This angle, combined with the presence of the solar wind electron *strahl* population (flowing only outward from the Sun), combined to produce an anisotropic series of electron distributions. Shown at left in **Figure 4** is a cartoon depicting the various electron velocity distributions that arise due to the presence of the lunar wake potential.

Notably, at points **B** and **C**, there exists the presence of counter-streaming electron beams (the *strahl* and a small fraction of the oppositely-directed core population), which is known to produce a variety of electrostatic turbulence and instabilities. Indeed, ARTEMIS P1 observed waves near the electron plasma frequency, indicative of such instabilities (**Figure 2, bottom panel**).

Figure 5



Ogilvie et al, 1996

WIND Lunar Wake Fly-by, 1994

In December, 1994, the WIND spacecraft executed a lunar fly-by at approximately 6.5 R_L downstream from the Moon and observed the lunar wake for the first time with modern instruments at a high data rate.

Motivation & Previous Work

Previous PIC Simulations of the Lunar Wake

Motivated by the WIND observations of electron density dropouts, increased electron temperatures and the presence of anti-parallel ion beams (**Figure 5**), 1-d PIC models have previously been applied to simulate the lunar wake. Not only have these simulations shown the existence of the above phenomena, but have also predicted additional effects, such as the presence of phase space holes and electrostatic instabilities (**Figures 6** and **7**).

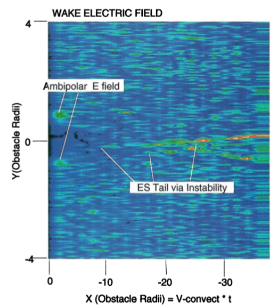


Figure 6 *Farrell et al., 1998*

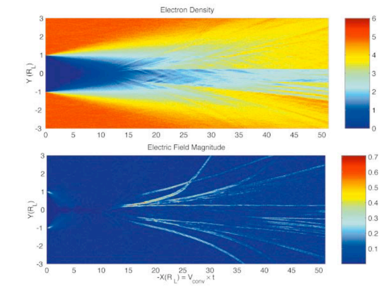


Figure 7 *Birch and Chapman, 2001*

Initial 1-d PIC Simulations

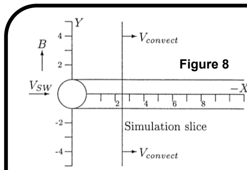


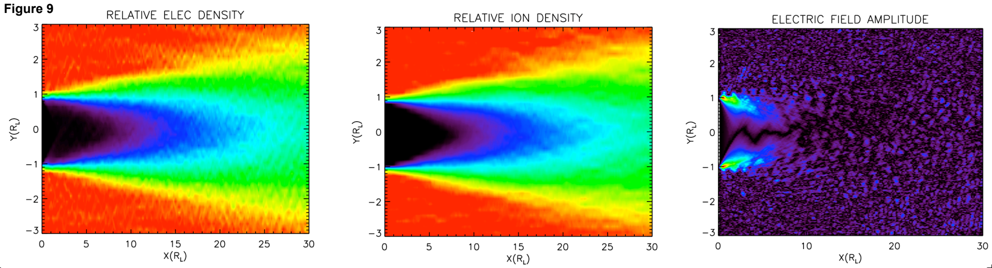
Figure 8

Farrell et al., 1998; Birch and Chapman, 2001

PIC Design and Initial Simulations

We have adapted a 1-dimensional particle-in-cell code previously used to study lunar surface charging on the dayside [*Poppe and Horányi, 2010; Poppe et al, 2011*] to model the ARTEMIS P1 measurements of the lunar wake. As shown at left in **Figure 8**, the code reproduces a quasi 2-d picture of the lunar wake by associating the simulation time with a convection distance past the Moon, assuming steady-state conditions [*Farrell et al., 1998; Birch and Chapman, 2001*]. Shown in **Figure 9** are the relative electron density, relative ion density and electric field magnitude in the lunar wake for *isotropic* solar wind electron distributions (ie., omitting the *strahl*). These initial results are similar to previous studies, showing the density depletion in both electrons and ions, as well as the presence of ambipolar electric fields.

Figure 9



Future Work

Initial 1-dimensional simulations of the lunar wake have reproduced basic characteristics previously modeled, including density dropouts and ambipolar electric fields. In order to fully understand the ARTEMIS P1 measurements of the February 2010 fly-by, we will continue to both benchmark the PIC code and successively add pertinent features, including the presence of an anisotropic solar wind electron *strahl* population. This will allow us to explore the role that such anisotropies have on electrostatic instabilities and waves in the lunar wake.

[1] K. W. Ogilvie et al., *Geophys. Res. Lett.*, **22**(10), 1996
[2] W. M. Farrell et al., *J. Geophys. Res.*, **103**(10), 1998
[3] P. C. Birch and S. C. Chapman, *Geophys. Res. Lett.*, **28**(2), 2001
[4] J. S. Halekas et al., *Space Sci. Rev.*, 2011
[5] A. Poppe and M. Horányi, *J. Geophys. Res.*, **115**, 2010
[6] A. Poppe et al., *Geophys. Res. Lett.*, **38**, 2011