Time-Dependent Hybrid Plasma Simulations of Lunar Electromagnetic Induction in the Solar Wind

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Wake Current Systems

what we know:
- wake forms on nightside due to dayside absorption and vacuum cavity
- wake current systems (incl. structure, extent) organize according to solar wind characteristics

\[ \mathbf{v}_{sw}, \mathbf{B}_{IMF}, n_e, n_i, T_e, T_i, \sigma(r), t \]

This study

Fatemī et al., [2014]
Holmstrom et al., [2012]
Static Hybrid Model Results

Dayside confinement, as predicted. Nightside fields are not confined within wake cavity. Strong induced field signatures in the deep wake near surface, especially with large IMF changes.

Fatemi et al., [2015]
Lunar EM Sounding - Transfer Function Method

The Apollo Picture

(a) TDEM Geometry

(b) Magnetotail Induction

(c) Solar Wind Induction

\[ \frac{\partial B}{\partial t} \]

Fuqua Haviland et al., 2019. ASR.
Transient Plasma Hybrid Kinetic Model

- Cell size: 50 km (≈0.028 RL)
- 16 macroparticles (only protons) per cell
- \( t_{\text{step}} = 0.001 \) s
- \( 0 < t < \approx 300 \) s, t=24 s IMF discontinuity
- \( \sigma_1 = 1.0 \times 10^{-8}, 1.0 \times 10^{-4}, 1.0 \times 10^{-3} \) [S/m]
- Conducting radius \( (r_1) = 1,600 \) km (≈ 0.91RM, or ≈ 32 cells), \( \sim M_{\text{ind}} = 1.64 \times 10^{17} \) A m\(^2\) (Fatemi et al., 2015; Saur et al., 2010).
- Resistive crust (1e-8 S/m) radius = 150 km (≈3 cells crust)
- Captures inductive and plasma response self-consistently

\[ V_{\text{sw}} = 320 \text{ km/s} \]
\[ n_{\text{sw}} = 6 /\text{cm}^3 \]
\[ \Delta B_y = -8 \text{ nT} \]
\[ T_{e,i} = 8.5 \text{ eV} \]
Results: Single Time Step

\( V_{SW} = 320 \text{ km/s} \)

\( n_{SW} = 6 \text{ /cm}^3 \)

\( \Delta B_y = -8 \text{ nT} \)

\( t = 50 \text{ s} \)
Results: Single Time Step (con’t)

\[ B_x, B_y, B_z \]

\[ |B| \]

\[ n_{sw} = 6 \text{ /cm}^3 \]

\[ \Delta B_y = -8 \text{ nT} \]

\[ t = 50 \text{ s} \]

\[ V_{sw} = 320 \text{ km/s} \]

\[ \Delta B_y = -8 \text{ nT} \]

\[ \sigma = 1.0 \times 10^{-8} \text{ S/m} \]

\[ t = 50 \text{ sec} \]

\[ \text{Difference} \]

\[ Y \] \[ Z \]

\[ X \]

\[ \text{Direction of disturbance} \]

\[ \Delta B_y = -8 \text{ nT} \]

\[ t = 50 \text{ s} \]

\[ \text{Fuqua Haviland et al., 2019. GRL.} \]
Results: Temporal effects

\[ \sigma = 1.0 \times 10^{-8} \text{ S/m} \]
\[ \sigma = 1.0 \times 10^{-4} \text{ S/m} \]
\[ \sigma = 1.0 \times 10^{-3} \text{ S/m} \]

\[ \Delta B_y = -8 \text{ nT} \]

\[ V_{sw} = 320 \text{ km/s} \]
\[ n_{sw} = 6 \text{ /cm}^3 \]

Fuqua Haviland et al., 2019. GRL.
Comparison to Analytic Theory

Observer 1, Full Fields

Key

Fields Difference

RMSE Fit

Fuqua Haviland et al., 2019. GRL.
Comparison to Analytic Theory

Observer 2, Full Fields

Key

- Green: $B_{\text{East}}$  - Blue: $B_{\text{Radial}}$
- Red: $B_{\text{North}}$  - Magenta: Reference
- Black: $B_{\text{ups-N}}$  - Cyan: Best Fit

Fields Difference

RMSE Fit

Key

- Green: $B_{\text{East}}$  - Blue: $B_{\text{Radial}}$
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- Black: $B_{\text{ups-N}}$  - Cyan: Best Fit

Fuqua Haviland et al., 2019. GRL.
Conclusions

• Vacuum theory alone is not able to fully characterize nightside induced fields. Some agreement on exponential time decay.
• Time-dependent plasma hybrid model is able to characterize plasma currents and induced fields which vary depending on solar wind conditions.
• Our model suggests enhanced nightside fields over theory.
  • Due to plasma-induced fields constructively add.
  • Compression of dayside induced fields at the terminator by SW ram pressure.
• Redefining Apollo era assumption about wake field confining induced field within cavity.
• We confirm that the inclusion of plasma interaction effects alongside inductive currents from a planetary interior yields results different than that from the vacuum response theory alone.
Questions?