Time-dependent MHD Simulation of the Lunar Core's Response to the Sudden Change in the Interplanetary Magnetic Field

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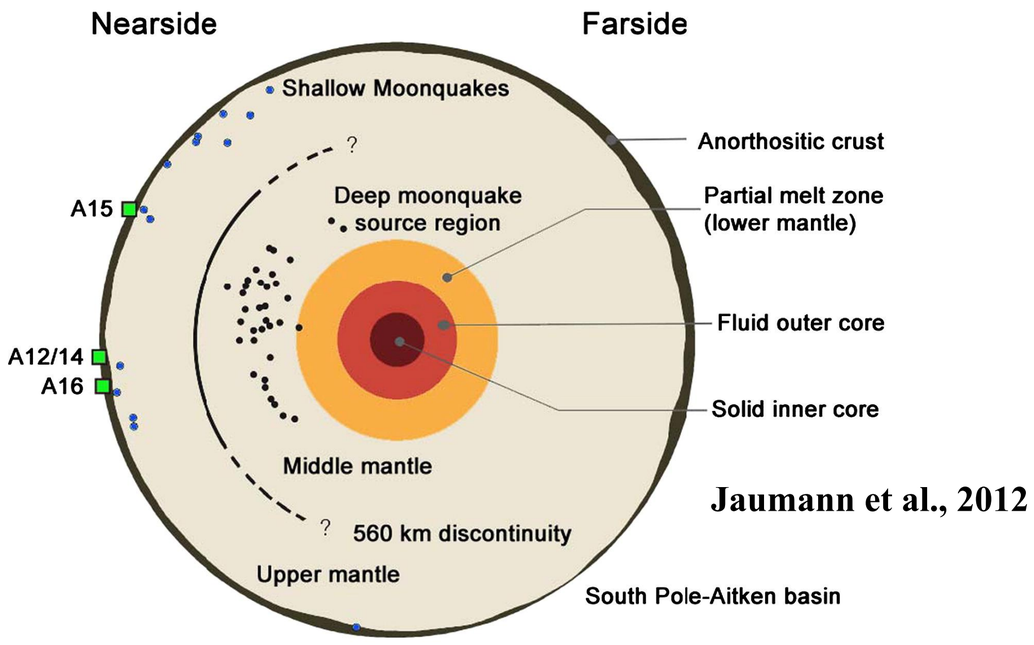
Introduction

As shown in the Figure, the Moon is a differentiated terrestrial planet, comprising a crust, a mantle, and a core.



Jaumann et al., 2012

The sudden change of the interplanetary magnetic field (IMF) serves as the primary driver of induced currents within the Moon's conductive interior. On the nightside, the interior induced magnetic fields can extend beyond the wake region, occasionally manifesting as lunar limb compressions.

Limb compressions are sporadic phenomena characterized by localized magnetic field and plasma compressions outside the boundaries of the lunar wake. Most studies correlate the compressional disturbance to the lunar crustal magnetic anomalies. The secondary possible source of limb compressions is thought to be the interaction of the solar wind with the lunar interior induced magnetic field during large IMF variation.

Method

Based on Block Adaptive Tree Solarwind Roetype Upwind Scheme (BATSRUS) code, we present a 3-D MHD simulation with a user-defined function. The details are shown below.

Governing Equations

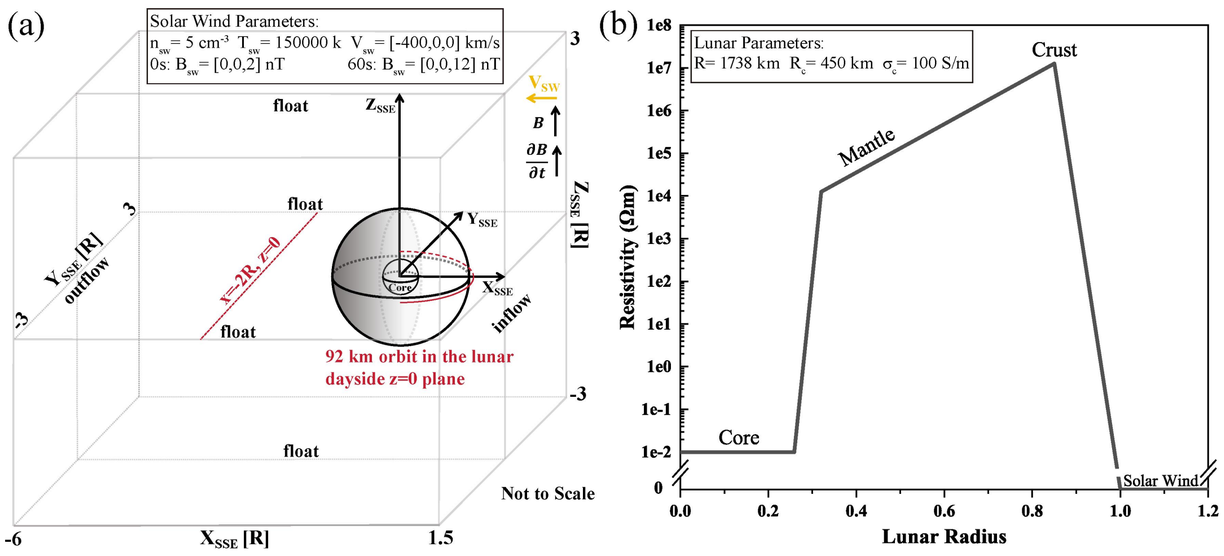
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \qquad \frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) + \nabla p - \boldsymbol{j} \times \boldsymbol{B} = 0$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(\mathrm{e} + \mathrm{p})\mathbf{u} + \frac{(\boldsymbol{B} \times \boldsymbol{u}) \times \boldsymbol{B}}{\mu_0}] = 0 \qquad \nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j} \qquad \nabla \cdot \boldsymbol{B} = \boldsymbol{0}$$

Outside the Moon: $\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{u}) = 0$

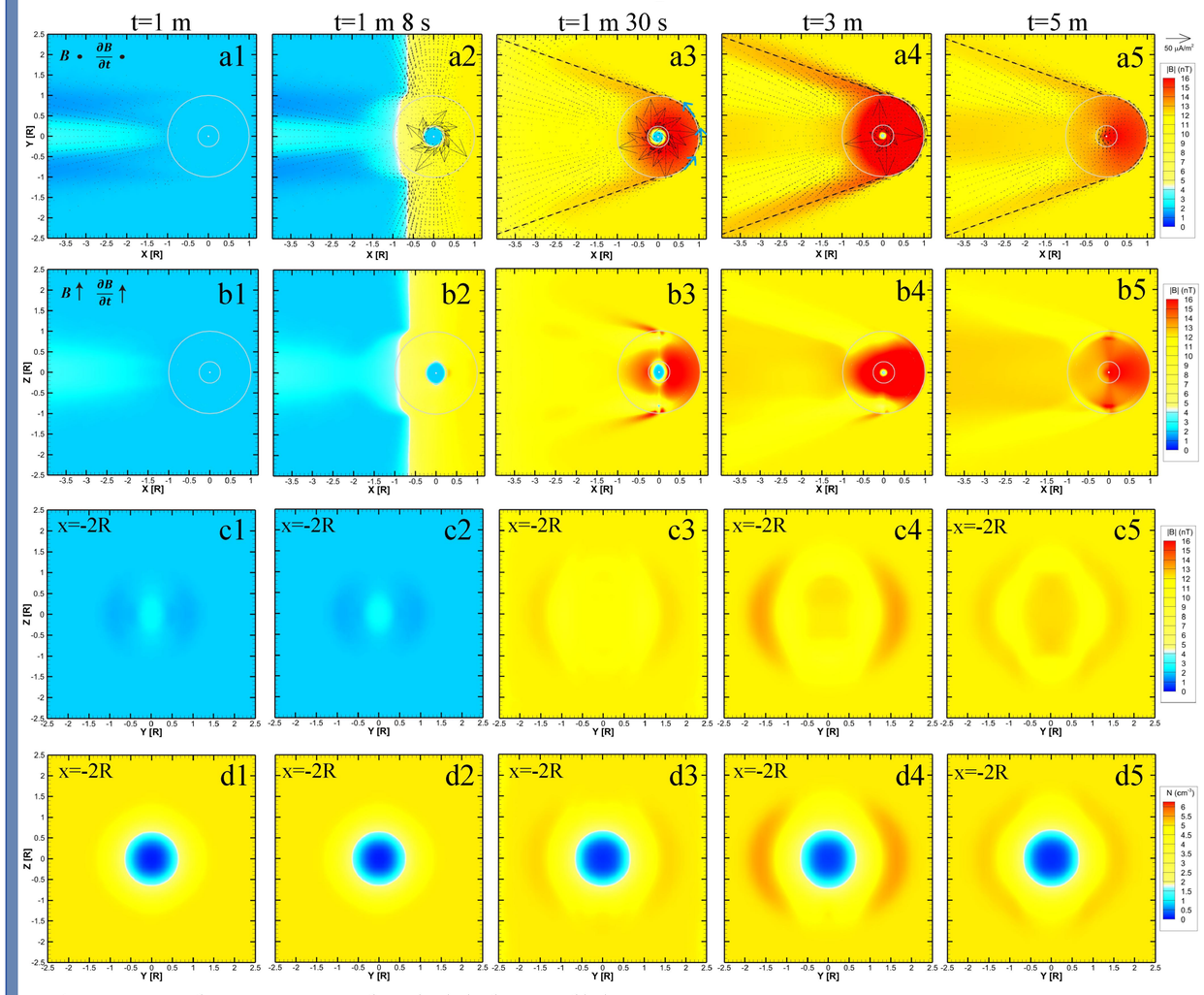
Inside the Moon: $\frac{\partial \boldsymbol{B}}{\partial t} + \frac{\nabla^2 \boldsymbol{B}}{\sigma \mu_0} = 0$

Initialization of the Simulation



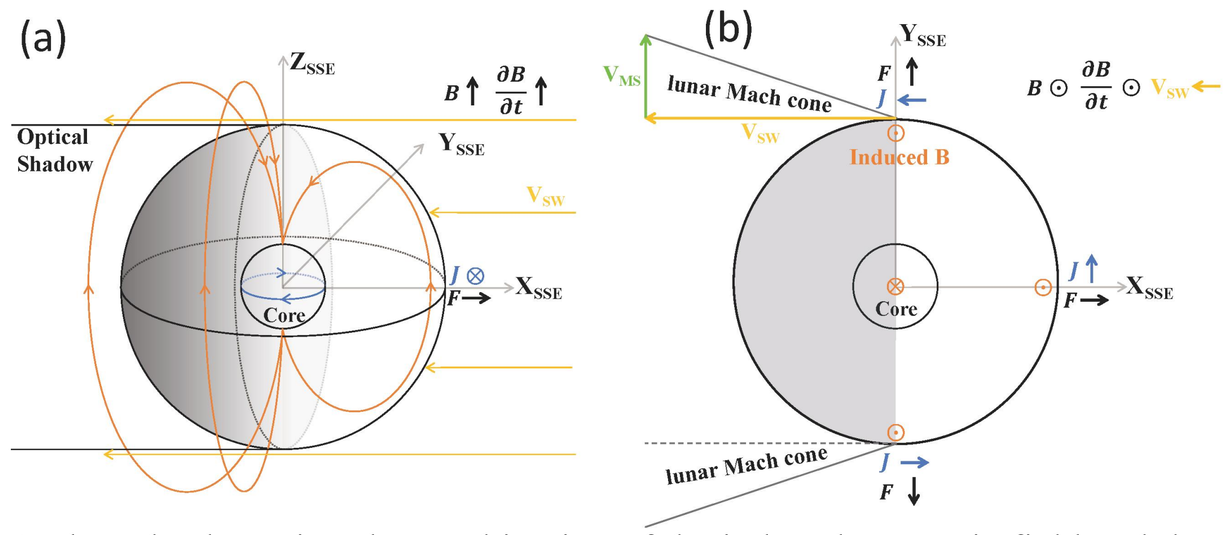
Result

Simulation Results at Different Time Steps



- 1 m: steady states under initial conditions
- 1 m 8 s: induced currents in the lunar core are already formed
- 1 m 30 s: the magnetic field enhancement below the lunar surface caused by the induced currents compresses the limb solar wind to produce limb compressions
- 3 m: limb compression signatures become stronger
- 5 m: limb compression signatures become weaker

Illustration of Physical Mechanisms



At the subsolar point, the combination of the induced magnetic field and the background magnetic field (both in the z direction) results in a stronger z-directed magnetic field within the lunar surface. This magnetic pressure gradient ($-\nabla P_B$) generates a y-directed current (J, shown by the blue symbol and arrow in the dayside lunar surface, creating a J × B force (F, illustrated by the black arrow) pointing radially outward along the x direction.

- The $-\nabla P_B$ cannot result in the lunar limb compression around the subsolar point, as the solar wind dynamic pressure is strong.
- Around the terminator, the normal component of the solar wind dynamic pressure is obviously lower, making the generation of the limb compression possible.

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