The Interaction Between the Moon and the Solar Wind

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Abstract

Bodies that lack a significant atmosphere and internal magnetic fields, such as the Moon, are obstacles to the solar wind. The solar wind ions and electrons directly impact the surface of the Moon due to the lack of atmosphere. Here we investigate the global Moon-solar wind interaction using a hybrid model (particle ions and fluid electrons). We focus in particular on the effects of non-uniform internal resistivity on the Moon-solar wind interaction. From seismic and magnetic field measurements it has been inferred that the Moon should have a conducting core, surrounded by a resistive shell. How does the presence of a core modify the solar wind interaction? Are the effects observable?

The hybrid equations

In the hybrid approximation, ions are treated as particles, and electrons as a massless fluid. The trajectory of the ions is computed from the Lorentz force, given the electric and the magnetic fields. The electric field is

$$\mathbf{E} = \frac{1}{\rho_I}\left(-\mathbf{J}_I \times \mathbf{B} + \mathbf{J} \times \mathbf{B} - \nabla p_e\right) + \eta \mathbf{J} - \eta_h \nabla^2 \mathbf{J}, \qquad (1)$$

where ρ_I is the ion charge density, $\mathbf{J}_I$ is the ion current density, p_e is the electron pressure, η is the resistivity, and η_h is a hyperresistivity. The current is computed from, $\mathbf{J} = \mu_0^{-1}\nabla \times \mathbf{B}$, where $\mu_0 = 4\pi \cdot 10^{-7}$ is the magnetic constant.
Then Faraday's law is used to advance the magnetic field in time,

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}.$$

Further details on the hybrid model used here, and the discretization, can be found in [1, 2, 4].

Vacuum regions and internal resistivity

In regions of low ion charge density, ρ_I, the hybrid method can have numerical problems. We see from (1) that the electric field computation involves a division by ρ_I. Thus, in low density regions we will have large electric fields, and in the limit of zero charge density, the electric field magnitude will tend to infinity. This can lead to numerical instabilities, due to large gradients in the electric field, and due to large accelerations of ions. The solution quickly becomes unstable.
However, a self consistent, physically correct way of handling the problem of vacuum regions was proposed a long time ago. Hewett noted that vacuum regions can be viewed as having infinite resistivity [5], and an algorithm can be devised where the resistivity in (1) is set to a large value in regions of low density.

In (1) we set $1/\rho_I = 0$ in vacuum regions and in the Lunar interior. This leads to the solution of a magnetic diffusion equation in such regions. For a constant resistivity we have that

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{\eta}{\mu_0}\nabla^2 \mathbf{B}.$$

This is similar to the heat equation and gives a time step limit for stability of

$$\Delta t < \frac{\mu_0 \Delta x^2}{2\eta},$$

where Δt is the time step for an explicit time integrator, and Δx is the cell size.
A minimum charge density parameter, $\rho_v = 0.0001$, decide what cells are vacuum. It is also possible to include arbitrary resistive obstacles, since the resistivity can be a function of position $\eta = \eta(\mathbf{r})$. Here we have chosen the vacuum resistivity of $\eta = 10^7\ \Omega$m, zero resistivity in free space, and a resistivity profile inside the Moon according to Fig. 1.

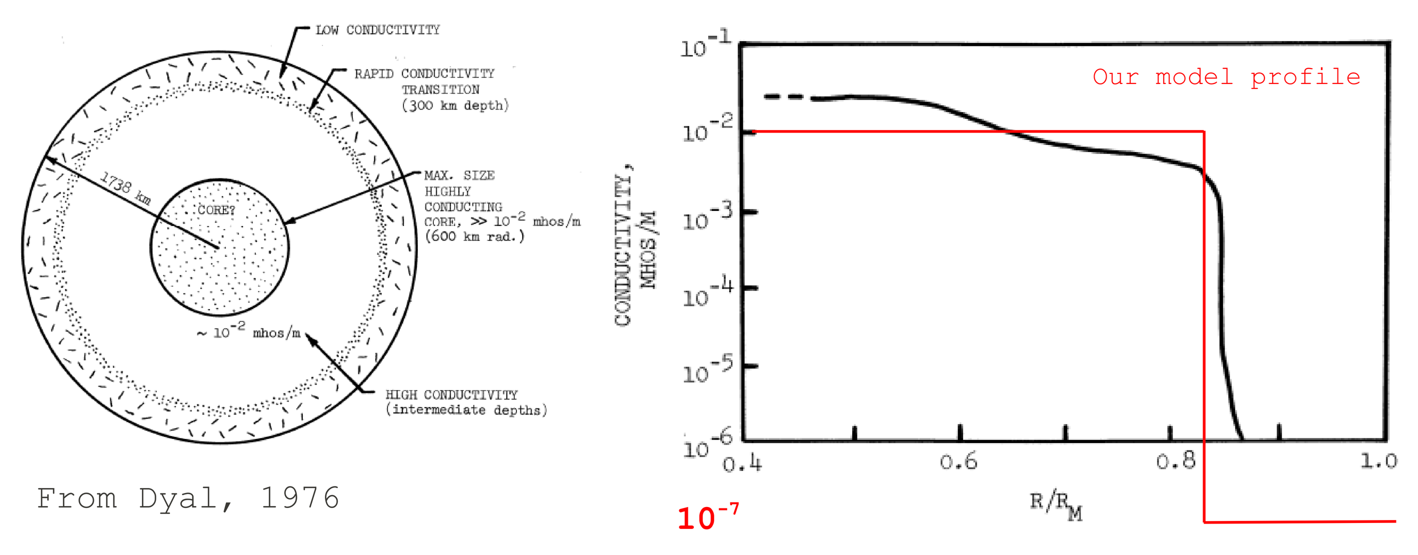

Figure 1: The Lunar internal structure from [6]. In red is shown the resistivity profile used in this work, A conductive core surrounded by a 300 km thick resistive shell. The existence of a Lunar core has been inferred from Apollo seismic measurements and magnetic field measurements.

Model setup

The interaction between the Moon and the solar wind was studied for a resistive obstacle in [3]. To investigate the global effects of a conducting core, according to Fig. 1, we study the interaction for typical solar wind parameters. The solar wind velocity is 400 km/s, the number density is 7 cm^{-3}, and the ion and electron temperature is $1 \cdot 10^5$ K. The interplanetary magnetic field (IMF) has a magnitude of 5 nT.
At the center of the Moon we have a dipole directed opposite to the IMF, with a strength such that the radial component of the total field is zero at the core radius. The effect of this dipole field is to expel the IMF from the core. Since the IMF changes on time scales much shorter than the time for the magnetic field to diffuse into the core, the IMF will be expelled from the core. The diffusion time can be estimated as $R^2\mu_0/\eta$, where R is the core radius. In our case this time is more than 7 hours.

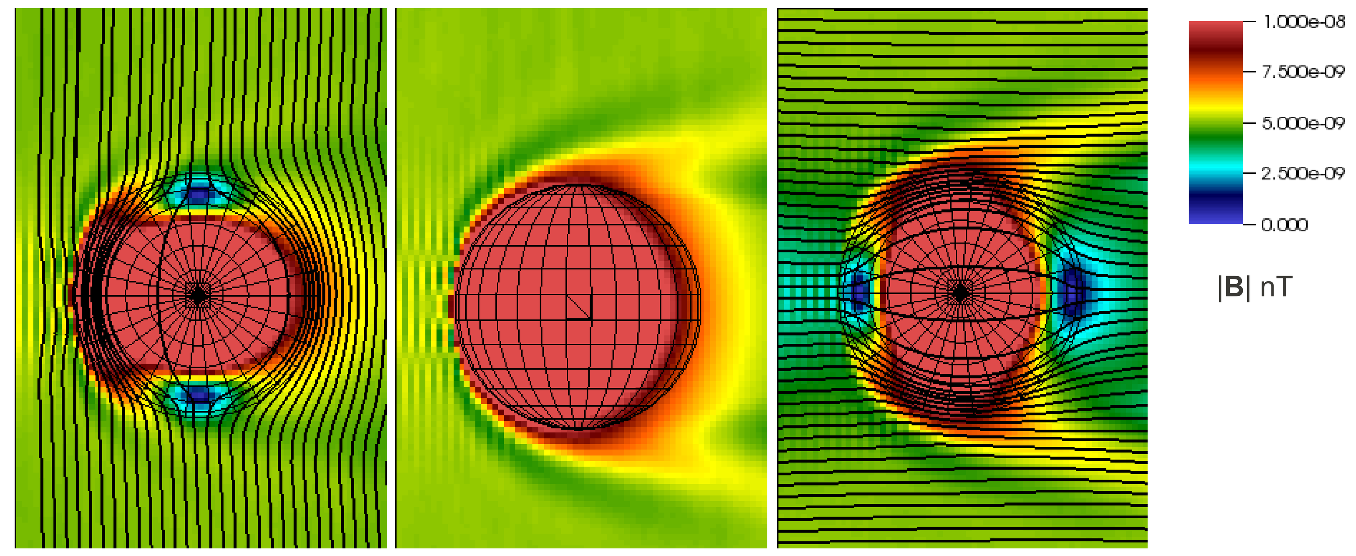

Figure 2: The magnetic field magnitude for a Moon with a core according to Fig. 1. The solar wind is inflowing from the left. The panels are cuts that go through the center of the Moon and contains the solar wind velocity vector. The left panel has the IMF perpendicular to the solar wind velocity and shows the plane that contains the IMF, which is shown by the black lines. The center panel shows the plane perpendicular to the IMF. The right panel shows a case when the IMF is parallel to the solar wind velocity.

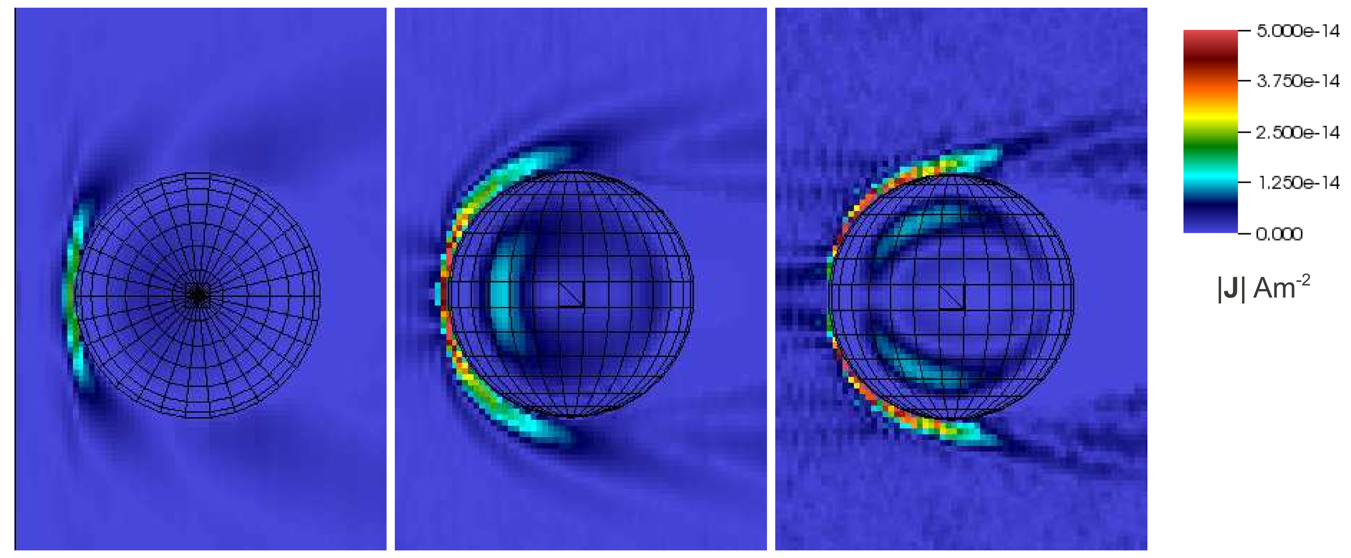

Figure 3: The current density magnitude for a Moon with a core according to Fig. 1. Each panel corresponds to the panel in Fig. 2.

Conclusions

- We have presented a hybrid plasma model that can handle vacuum regions and obstacles of arbitrary resistivity
- The presence of a conductive core can modify the wake region, but can also have effects on the dayside magnetic field
- Constraints on the Lunar core size and the conductivity of the mantle can in principle be obtained from comparing observations with models of the global solar wind interaction
- Ongoing work is to investigate the effects of different internal resistivity profiles and changing solar wind conditions

References

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