IMPACT-GENERATED MAGNETIC FIELDS ON THE MOON: A MAGNETOHYDRODYNAMIC NUMERICAL INVESTIGATION.

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Introduction:. Natural remanent magnetization has been identified in lunar rocks, the lunar crust, and a diversity of meteorites. Much of this magnetization is thought to have been produced by cooling a core dynamo magnetic field [1]. However, the identification of lunar crustal magnetic anomalies at the antipodes of four of the five youngest large (>600 km diameter) impact basins [2-5] has motivated the alternative hypothesis that the lunar crust could have been magnetized by the impacts. In particular, it has been proposed that highly conducting ionized vapor produced by a basin-forming impact interacts with the ambient solar wind plasma surrounding the Moon to amplify the ambient solar wind magnetic field or any core dynamo field [6-9]. As the ionized vapor cloud expands around the Moon, it pushes and compresses the solar wind plasma into a small region at the antipodal point. The conservation of magnetic flux then leads to an enhanced magnetic field in the compressed plasma. This field can then be recorded as shock remanent magnetization by crustal materials at the antipodal point following the impact of converging basin ejecta.

A key requirement for the impact-generated fields hypothesis is that the compressed field be sufficiently strong to explain the lunar paleointensities (at least tens of μT) and maintained at the antipodal point for a sufficiently long time (several hours) for the ejecta to arrive and impact the surface. Previous hydrodynamic simulations of the expansion of the vapor cloud [8,9], found that the enhanced field will be strong enough (perhaps reaching hundreds of μT) and will remain at the antipodal site for a sufficiently long time (>1 day) for the arrival of incoming ejecta. However, these studies did not involve an explicit and self-consistent calculation of the magnetic field interaction with the plasma. Rather, the cloud expansion rate and shape at certain times were taken from the hydrodynamic simulation, and the effects on the magnetized plasma were estimted using theoretical arguments.

The coupled evolution of the vapor and a magnetized plasma may be more complex than the picture presented in [8,9]. As the cloud expands, its density, pressure and velocity change with time and location. The non-uniform cloud structure should be taken into account in assessing the level of compression and its duration. Another open question pertains to the level of penetration of the magnetic field into the initially non-magnetized vapor. If some of the magnetic flux diffuses into regions dominated by the vapor, then less flux will be transported to the antipodal region. These limitations call for a fully coupled calculation of the gas dynamics and electrodynamics of the system.

A natural framework for describing magnetized space plasmas self-consistently is the system of magnetohydrodynamic (MHD) equations. The development of high performance MHD codes in the last decade allows us to revisit these previous important studies. Our goal is to perform two-dimensional (2D) and three-dimensional (3D) MHD simulations simulations of a vapor cloud embedded within a background solar wind, and to examine how these will effect the previous estimations of the strength and duration of the magnetic field enhancement at the antipodal points. The MHD simulations will also allow us to estimate the importance of removal of magnetic flux due to reconnection and continuous viscous drag imposed by the solar wind, and of MHD instabilities. This will help in assessing how likely it is for impacts to trigger remnant crustal magnetization.

Method: We use BATS-R-US [9], a highly parallelized, 3D MHD code, to simulate the coupled evolution of the vapor cloud and the magnetized solar wind plasma. BATS-R-US is capable of simulating ideal- and resistive-MHD regimes, as well as a single fluid or several fluids/species. Our effort currently focuses on the plasma phase of the cloud and does not aim to model the formation of the cloud from the impact itself. The initial cloud properties are taken from detailed impact simulations appearing in the literature.

We will consider different MHD processes, such as: 1) the finite resistivity of the lunar mantle 2) magnetic diffusion between the solar wind and the initially non-magnetized cloud, 3) magnetic reconnection at the antipode, and 4) the transport of magnetic flux due to solar wind motion. This will allow us to systematically examine whether impact-generated fields can indeed be responsible for the formation of crustal field enhancements on the Moon.

Preliminary Results: We performed a simplified MHD simulation describing the expansion of a cloud of dense plasma withing a uniform background plasma. The initial magnetic field is uniform at 4 nT and directed along the *x*-axis. The background number density and temperature are 9 particles per cm^3. and 100,000K, respectively, which is typical of the solar wind. The initial cloud is located above the lunar surface along the *y*-axis. The cloud evolves due to thermal expansion and gravity. The Moon is assumed to be an insulator and the lunar surface is assumed to be an impenetrable wall with respect to the plasma flow.

Figure 1 shows a snapshot from the simulation, depicting the magnetic field magnitude (top) and the plasma density (bottom) in a plane containing the plasma cloud. The black curves trace magnetic field lines. The most prominent effect on the magnetic field is its convection and compression due to the cloud expansion, consistent with the simplified model presented in [8, 9]. Regions of strong magnetic field appear in the flanks of the expanding cloud. As time progresses, the cloud sweeps the solar wind magnetic field into smaller and smaller regions. This result was obtained by neglecting the solar wind flow speed, while the initial vapor cloud has a density that is only one order of magnitude higher than the background wind. A more realistic density, using initial cloud parameters from [8, 9], is of the order of 6 g/cm^3, which is many orders of magnitude higher than the ambient wind density (1x10^{-17} g/cm^3). Thus this result only serves as a proof of concept.

We performed a purely hydrodynamic simulation using the same vapor density as in [7]. We found that a substantial portion of the initial vapor mass acquire speeds higher than the escape velocity of the moon (2.4km/s). This raises the question of how much of the vapor will converge at the antipodal point, and whether it will remain bound to the moon for a long enough time to allow remnant magnetization to take place. The final stages of the cloud convergence were not included in the hydrodynamic simulations used in [7] and [8]. We will examine this issue carefully, as the higher speeds may be a result of numerical diffusion, or the neglect of the interaction of the vapor with other ejected material, etc.

Discussion: We will address several outstanding questions regarding the interaction of vapor clouds with the solar wind environment around the moon. This is the main building block of theories relating the compression of the magnetized solar wind to lunar remnant magnetization. The basic question relates to the convergence of the vapor on the antipodal point and the time the compressed magnetic field will be maintained there. Further, in the present simulations the plasma environment was assumed to be stationary. We will take into account the wind flow speed in order to will to study the cloud's expansion in the lunar wake or inside the supersonic and super-Alfvénic wind flow. In the latter case, a shock will form in front of the cloud, increasing the level of field compression. Furthermore, the fact that the wind is continuously flowing past the Moon at ~400 km/s may also play a crucial role, as it will drag the magnetic field lines that are connected to the open field lines of the solar wind away from the antipodal site at time scales smaller than the several hours required for remanent magnetization to be effectively created. Finally, the compressed field lines from both sides of the antipodal point will have opposite polarities, and may form an X-line configuration and reconnect, resulting in removal of magnetic flux.

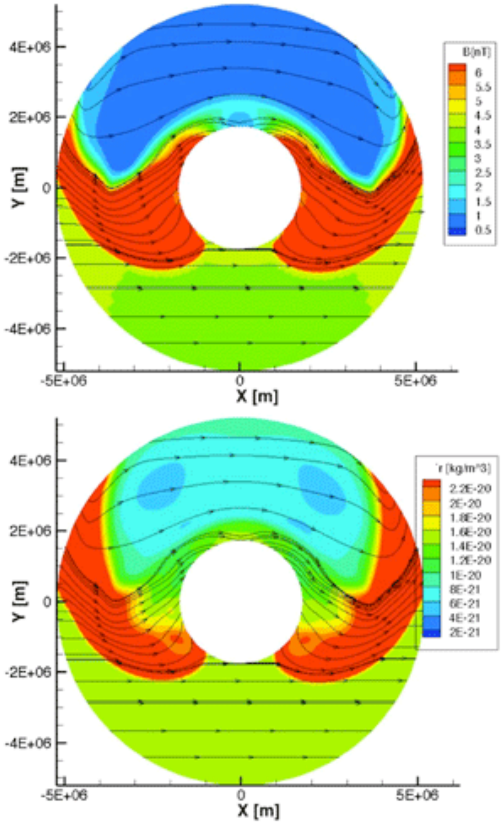

Figure 1: Magnetic field magnitude (top) and plasma density (bottom). The inner white circle represents the Moon.

Summary: We present a systematic study of the interaction of impact-driven vapor clouds with the ambient solar wind around the Moon. The MHD simulations will help bridge the gap between our understanding of the vapor and melt evolution in the hydrodynamic limit and the different possible mechanism responsible for remnant magnetization in the lunar crust.

References:

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