CAN IMPACT-AMPLIFIED MAGNETIC FIELDS BE RESPONSIBLE FOR MAGNETIZATION ON THE MOON?

R. Oran[1], Y. Shprits[1, 2], and B. P. Weiss[1], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA (roran@mit.edu), [2]Department of Earth and Space Sciences, University of California Los Angeles, Los Angeles, California, USA.

Introduction:. Although the Moon presently does not have a core dynamo, spacecraft measurements have revealed the presence of remanent magnetization in the lunar crust. The formation of the crustal magnetic anomalies remains uncertain. A key question is whether the crustal magnetization is a record of past intrinsic fields [1] or whether they were created by external fields. The latter origin would have broad implications for our understanding of the Moon's thermal history and internal structure because it would mean that a dynamo is not required to explain the anomalies. The lunar crustal field also serves as a test case for understanding magnetization of other solar system bodies, such as Mars, Mercury, and asteroids.

The identification of strong anomalies at the antipodes of the youngest large impact craters [2-5] led to the hypothesis that the impacts may be responsible for the magnetization of the crust. In this scenario, ionized vapor clouds, generated by the impacts, interact with the surrounding solar wind and compress it toward the antipodal point. The compressed solar wind will carry an amplified magnetic field that is subsequently recorded by shocked and heated lunar rocks.

The impact-amplified fields hypothesis has been studied for several decades using hydrodynamic and impact simulations [6-9]. Although the evolution of the ionized vapor and the molten ejecta have been studied in increasing detail, all simulations thus far did not model magnetic fields. To address this gap, we have conducted the first magnetohydrodynamic (MHD) simulations of impact-generated plasmas on the Moon. In the MHD approximation, both gas dynamics and electrodynamic processes are solved self-consistently. Our aim is to determine whether impact-generated vapor clouds could indeed magnetize the lunar crust.

Objectives: For impact-amplified fields to be responsible for the magnetization, this mechanism must be able to 1) produce a sufficiently strong antipodal field and 2) maintain the field for a sufficiently long time. We discuss these requirements separately. First, the field strength required to explain the antipodal magnetic anomalies should be in the range of 10-100 μT (given the known magnetic properties of the lunar crust [1] assuming that the crust contains a thermoremanence or shock remanence). In comparison, the ambient solar wind field at the Moon has a present-day value of only $\sim 7\times10^{-3}$ μT (although it may have been as a strong as $\sim 30\times10^{-3}$ μT for a younger Sun). It follows that an amplification of about three orders of magnitude is required for the hypothesis to hold. Second, the amplified field must be maintained at the antipodal point to allow for the ejecta to arrive and impact the surface (which occurs several hours after the impact). Previous studies [8, 9] used general geometric argumants but no detailed simulations to estimate that impacts could indeed produce the required field amplification and duration. The cloud's shape at certain times was estimated from a hydrodynamic simulation and the resulting magnetic field topology for each snapshot was derived schematically. Although this procedure is insightful and could produce a globally realistic evolution, it could not account for additional processes such as non steady-state solar wind flow, magnetic tension, reconnection at the antipode, and realistic magnetic diffusion inside the Moon. These processes yield a much more complex evolution and should be directly and self-consistently simulated in order to examine the validity of this hypothesis.

Numerical Model: A natural framework for describing the coupled evolution of ionized gases and electromagnetic fields is the system of MHD equations. The recent advent of high performance MHD numerical codes allows us to revisit the impact-amplified fields hypothesis. Our goal is to perform two-dimensional (2D) and three-dimensional (3D) MHD simulations of a hot and dense vapor cloud at the lunar surface surrounded by a background solar wind. The MHD simulations allow us to explicitly model the evolution of the magnetic field topology due to advection, compression, and diffusion. This, in turn, allows us to estimate the removal of magnetic flux due to high expansion speeds (above the escape velocity), reconnection, and continuous viscous drag imposed by the solar wind.

We used BATS-R-US [10], 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 and species. We used BATS-R-US to implement a coupled model of the solar wind, Moon, and vapor. The Moon is assumed to be either a perfect insulator or variably resistive layered lunar interior. For the latter case, we allowed the magnetic field to diffuse inside the body. The boundary condition at the lunar surface is set such that the solar wind is absorbed, while the surface serves as an impenetrable wall for the much denser vapor. The magnetic field is continuous across the lunar surface and inside the body, but no magnetic field can penetrate the highly-conducting core.

The model is initialized with a uniform solar wind flowing past the Moon. After the flow reaches a steady-state (exhibiting a wake in the downstream direction, and diffusion of magnetic flux into the Moon), a cylindrical vapor cloud is placed just above the lunar surface. Our effort currently focuses on the plasma phase of the vapor and does not aim to model the formation of the cloud from the impact itself. The initial vapor properties are taken from impact simulations appearing in the literature. The solar wind density and temperature used are typical for those observed near the Earth.

We will consider different MHD processes, such as the finite resistivity of the lunar crust and mantle, magnetic reconnection at the antipode, and the transport of magnetic flux due to cloud expansion andsolar wind motion. This will allow us to systematically examine whether impact-amplified fields can be responsible for crustal magnetization on the Moon.

Results: We performed a series of MHD simulation describing the expansion of the vapor within a uniform background solar wind. The vapor evolves subject to thermal expansion and the lunar gravity. The vapor pressure is much higher than the solar wind gas and magnetic pressure and thus the magnetic field does not significantly effect the vapor flow. Accordingly, the solar wind magnetic field is very easily pushed and compressed due to the vapor expansion.

We investigated several possible geometries of the solar wind flow direction and magnetic field direction. We also varied the solar wind field strength to examine the effects of a hypothetical stronger solar magnetic field that may have existed during the impact period.

Figure 1 shows snapshots from one of these simulation, depicting the plasma density (top) and magnetic field magnitude (bottom) in the impact plane, for two different times. 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 vapor sweeps the solar wind magnetic field into smaller and smaller regions. Importantly, a substantial portion of the initial vapor mass acquire speeds higher than the escape velocity of the moon (2.4 km/s). This limits how much of the vapor will converge at the antipodal point and how much pressure will be available to confine the field there. Finally, the compressed field lines from both sides of the antipodal point have opposite polarities, and they form an X-line reconnection site (inside the red box on the top right panel) to the left of the antipode, resulting in the removal of additional magnetic flux. In this particular simulation, the field amplification reaches no more than 10 nT

Discussion: Our initial results show that the vapor expansion and wind compression lead to only moderate field enhancements. In the most favorable case, the field was amplified to 0.2μT, which is several orders of magnitude below the required value of 10-100 μT (see(1) above). The convergence at the antipode occurs around an hour after the impact, which satisfies (2). This would in principle allow the compressed field to be maintained. The main physical mechanisms limiting the antipodal field strength is the large expansion speeds and reconnection, which together work to remove magnetic flux. The expansion speed (~50-60km/s) experienced in the beginning of the expansion, far surpasses the escape velocity of 2.4km/s. This causes a significant amount of material to be lost, while pushing the magnetic field away. This process may be less effective at flux removal if the interaction of the vapor with the ejected melt is considered, which should slow down the expansion [9]. We are currently studying these processes in more detail.

Based on these results, we propose that impacts are probably not the cause of magnetization on the lunar crust, and that the source of magnetization is more likely to be an internal core dynamo. This implies that the Moon formed an advecting metallic core in its early history.

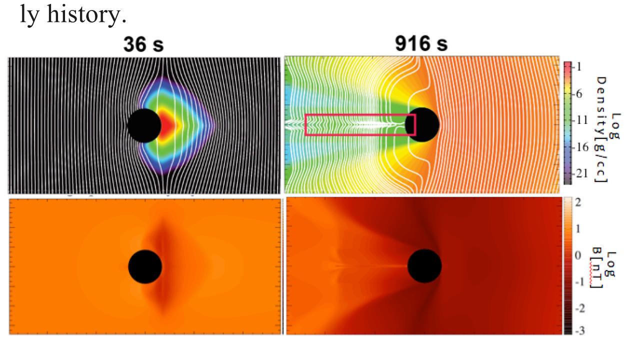

Figure 1 Plasma density (top) and magnetic field magnitude (bottom). The black circle marks the Moon. White curves trace magnetic field lines (line density does not denote field intensity).

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