FORMATION OF MAGNETIC ANOMALIES ANTIPODAL TO LUNAR IMPACT BASINS: IMPROVED NUMERICAL AND ANALYTIC ANALYSIS. L. L. Hood[1] and N. A. Artemieva[2], [1]Lunar and Planetary Lab, University of Arizona, Tucson, Arizona 85721; lon@lpl.arizona.edu, [2]Institute for Dynamics of Geospheres, Moscow, Russia, artemeva@psi.edu.

Introduction: The largest concentrations of strong lunar crustal magnetization occur in regions antipodal (diametrically opposite) to the youngest large basins including Imbrium, Orientale, Serenitatis, and Crisium [1,2]. Previous work has suggested that transient magnetic field generation and amplification peripheral to the expanding (partially ionized) vapor cloud could have led to a temporary increase in field intensity in the antipodal region [3,4]. Formation of magnetization sources in these regions during the period of compressed field amplification was then attributed to either: (a) residual heating during basin ejecta deposition; or (b) shock effects associated with the convergence of seismic compressional and/or surface waves [4]. In this paper, the conditions that may have led to crustal magnetization antipodal to lunar basins is examined further using recent detailed numerical simulations of ejecta deposition and expansion around the Moon of partially ionized vapor clouds produced in hypervelocity basin-forming impacts. In addition, methods are developed for estimating the range of intensities of the initial, ambient magnetic field that would allow strong magnetizing fields to have persisted in the antipodal zone for a time sufficient to allow magnetization acquisition. The latter range is important for determining whether or not a lunar core dynamo field is necessary for explaining the observed magnetization.

Impact Model Calculations: A series of numerical simulations was carried out with the 3D0 hydrocode SOVA [5] coupled to tabular versions of the ANEOS equations of state for materials of interest. SOVA is a two-step Eulerian code developed at the Institute for Dynamics of Geospheres that can model multi-dimensional, multi-material, large deformation, strong shock wave physics. The product of calculations of this type is a time sequence of vapor cloud evolution and interaction with the Moon for a range of impactor compositions and initial conditions. Internal energy densities, mass densities, ionization fractions, and effective scalar electrical conductivities are calculated in 3D as a function of spatial location in the impact vapor cloud. Besides their thermodynamic history, the simulations also provide the final distribution of impact ejecta on the lunar surface.

Figure 1 shows the vapor cloud mass density distribution at times of 500 and 1000 seconds following a 15 km/s impact at an angle of 30^o from the horizontal. The scale bar indicates the logarithm of the density in gm/cm^3. At this time, the leading shock fronts have moved more than half way around the Moon and are beginning to converge in the antipodal region. Additional runs will determine the sensitivity of these results to the assumed impact angle and other impact parameters.

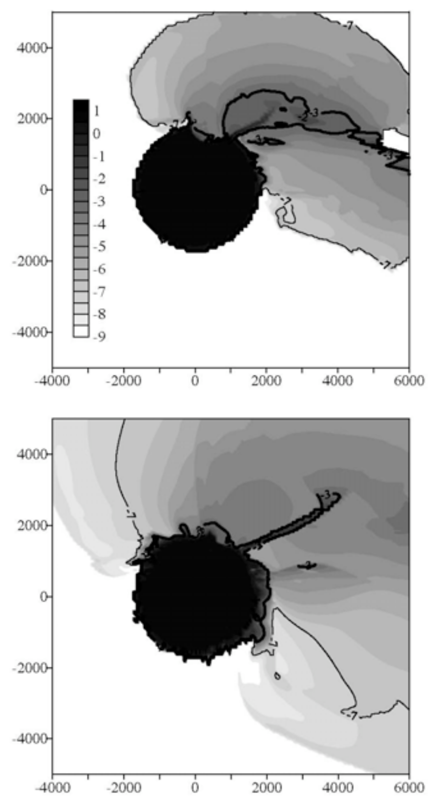

Figure 1

Impact Ejecta Distribution: For the case of a vertical impact, only a small fraction of molten ejecta is deposited in the hemisphere opposite to the impact point. For a 30^o from horizontal impact, more ejecta is deposited in the antipodal hemisphere. However, in neither case is there a local maximum of ejecta deposition at the antipode itself. These results differ from earlier calculations [6], which assumed all material was ejected at an angle of 30^o from the horizontal. In the present simulations, the ejection angle is usually higher than 50^o.

Magnetization Mechanisms: According to the results of Figure 1, the vapor cloud produced in a 15 km/s basin-forming impact will require ~ 1500 seconds to reach the antipodal region. Impacts at higher velocities (up to 30 km/s) will likely require at least 750 seconds to reach the antipode. These times are significantly longer than those calculated previously [4]. For comparison, seismic compressional waves traveling through the lunar mantle have typical velocities near 8 km/s and would therefore converge at the antipode at times ranging from approximately 430 to 680 seconds, i.e., before the period of maximum compressed field amplification. Seismic surface waves with velocities of slightly more than 1 km/s would arrive in approximately 80 minutes. The first antipodal arrival times of basin ejecta range from 0.5 to 1.5 hours, depending on ejection angle. However, according to the present simulations, no significant ejecta deposition occurs in the antipodal region. If these results are correct, then it appears that only seismic surface waves would arrive in the antipodal region during the period of maximum compressed field amplification.

Compressed Magnetic Field Amplitude: In order to calculate the magnetic field outside the vapor cloud during its expansion around the Moon, we first assume that a finite density of partially ionized gas exists near the surface (resulting, for example, from a transient impact-generated ionosphere). For ambient gas temperatures of ~ 1000 K and a mean molecular weight of ~16, the sound speed is $v_S \sim 0.85$ km/s. The Alfvén speed in the ambient ionized gas is given by $v_A = (B^2/8\pi\rho)^{1/2}$, where B is the magnetic field strength and ρ is the gas mass density. For $\rho > 10^{-12}$ gm/cm^3 and B < 1000 nT, $v_A < 0.2$ km/s. Therefore, the magnetosonic speed ($= (v_s^2 + v_A^2)^{1/2}$) will be less than 1 km/s, which is much less than the expansion velocity of the vapor cloud (> 2 km/s). In this situation, the vapor cloud expands at a supermagnetosonic velocity and an MHD shock wave will be present upstream of the outer periphery of the vapor cloud.

Upstream of the shock front, the ambient magnetic field and ambient ionized gas remain unperturbed. Between the shock front and the outer periphery of the vapor cloud, both the magnetic field and the ambient gas are compressed. As the MHD shock fronts converge in the antipodal region, the magnetic field intensity (and gas density) are increased further. Convergence continues until the total pressure (magnetic pressure plus thermal gas pressure) becomes comparable to the dynamic pressure of the expanding vapor cloud at its periphery. According to the results of Figure 1, the impact vapor gas density at the outer periphery of the vapor cloud near the Moon is ~ 10^{-9} gm/cm^3 and the expansion velocity is ~ 2 km/s. The dynamic pressure is therefore ~ 40 dynes/cm^2. Neglecting the compressed thermal gas pressure, the magnetic pressure, $B^2/8\pi$, should therefore be of the same order to prevent further convergence of the impact vapor.

A first estimate for the magnitude of the magnetic field intensity in the antipodal zone relative to the initial field intensity can be obtained from the condition that the total magnetic flux passing through the lunar surface on the antipodal side should be conserved during the convergence of the impact vapor. The field intensity is therefore proportional to the ratio of the surface area of the antipodal hemisphere to the area of the surface enclosed by the converging vapor: $B \sim B_o(2\pi R_M^2/\pi R_C^2)$, where B_o is the initial ambient magnetic field strength, R_M is the lunar radius, and R_C is the radius of the region enclosed by the converging vapor cloud. For $R_C \sim$ 400 km, $B \sim 38B_o$. From these results, we find that B_o should be > 0.8 G (0.08 mT) to ensure a stand-off of the expanding impact vapor in the convergence zone, which would then allow persistence of the period of compressed field amplification for ~ 1 hour or more.

Summary and Conclusions: According to the numerical simulations reported here, the convergence at the antipode of seismic surface waves is the most likely magnetization mechanism that could have operated directly during the period of compressed field amplification. This would require a persistence of the magnetizing field for a period of at least ~ 1 hour after the impact. This can be achieved through a stand-off of the converging vapor cloud only if the initial ambient field was relatively strong (at least several tenths of a Gauss). Such a stand-off is also more consistent with observational evidence that antipodal magnetized regions are at least ~ 10^o in extent [1,2].

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