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MAGNETIC EFFECTS OF LARGE-SCALE IMPACTS ON AIRLESS PLANETARY BODIES. L. L. Hood and Z. Huang, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721.

Background: The analysis of lunar orbital and sample data combined with laboratory measurements of impact-produced plasmas suggest that large-scale impacts on planetary surfaces may have had significant magnetic effects[1,2]. These effects may potentially explain part or all of lunar crustal magnetization and, by extension, may be responsible for producing paleomagnetism on other airless silicate bodies in the solar system. We report here further theoretical studies of the magnetic field and remanent magnetization effects of basin-scale impacts on the Moon. The specific case of a Moon exposed to the solar wind plasma flow and its embedded magnetic field is treated. It is shown that maximum compressed field amplitudes occur antipodal to the impact point in agreement with the observed tendency for orbital magnetic anomalies to be concentrated antipodal to young large lunar basins[3]. Generalization of these results to include magnetic effects of impacts on other airless or nearly airless planetary bodies in the solar system (e.g., Mercury and outer planet satellites) is the subject of current work but is not specifically addressed here.

Model Calculations: To provide a basis for calculating magnetic field effects, numerical models of the vapor plume expansion following a basin-scale impact on a lunar-sized spherical body were constructed. An initial calculation was performed for a gabbroic anorthosite impactor and target using only an ideal gas equation of state; partial condensation of the vapor during the cloud expansion was therefore not accounted for. (Later work including the effects of partial condensation did not produce major alterations of the cloud evolution.) Initial conditions were set for a 15 km/s vertical impact using peak shock states and pressure thresholds for incipient and complete vaporization.[5] The initial specific internal energy was 2.8×10^{11} erg/gm and the initial mass density was 6.43 gm/cm^3. Approximately 41% of the material exposed to peak shock pressure was estimated to be vaporized. As a first approximation to the radial decay of shock pressure from the impact point, it was assumed that the peak pressure applies out to a distance of $\sim$ 2 impactor radii beyond which the pressure falls to zero. Under these assumptions, a spherical impactor with radius 68 km produces a total vaporized mass of 2.77×10^{22} gm and a final basin diameter of about 912 km according to the Schmidt-Holsapple scaling law. Results showed that expansion of the vapor cloud periphery occurs at a velocity comparable to or somewhat larger than the impact velocity. For example, after 64 seconds, the cloud periphery has expanded approximately one-third of the way around the Moon. The mass density within the cloud falls off exponentially with radial distance while the specific internal energy is relatively constant but decreases monotonically with time. After approximately 410 seconds, the outer periphery of the cloud had begun to converge at the antipode of the impact point.

Magnetic Field Effects: Using the output of the vapor cloud calculations described above, the possible modes of magnetic field amplification and generation in basin-scale lunar impacts were investigated. Impact field generation mechanisms can be divided into two classes: (1) Spontaneous field generation within the impact plasma cloud due to thermal pressure gradients[1]; and (2) field generation external to the cloud as the expanding ionized gas encounters ambient plasmas and fields.[2]

Transient electrical currents are generated in the plasma cloud itself by strong temperature and density gradients combined with the basic difference in ion and electron mobilities. A scaling analysis of the governing equations yielded an estimate for the saturation magnetic field amplitude, $| B_s | \sim (ck/e)(\Delta T/VL)$, where c is the speed of light, k is Boltzmann's constant, e is the electron charge, $\Delta T/L$ is a typical cloud temperature gradient, and V is a representative gas expansion velocity. Although generated field amplitudes can be large for laboratory-scale events, $| B_s |$ decreases as L increases while ΔT and V remain relatively constant. In the basin-scale impact plasma cloud calculation described above, after 64 seconds the size of the cloud is comparable to the lunar diameter. Maximum temperatures near the impact point are $\sim 10^4$K and decrease to much smaller values in a distance of $\sim$ 1000 km. Typical expansion velocities are $\sim$ 10 km s^{-1}. Substitution into the above expression yields $| B_s | \sim 10^{-6}$ G. Even at times of < 10 seconds after the impact, the estimated field amplitudes remain $< 10^{-4}$ G. It is therefore concluded that large-scale impacts on airless planetary surfaces are unlikely to produce significant large-scale magnetizing fields within the impact plasma cloud itself.

Thus far, we have undertaken one calculation of external field generation for a simplified but realistic ambient lunar plasma environment. The results are summarized in the Figure. The environment considered is the case in which the Moon is directly exposed to the outflowing solar wind plasma and its embedded magnetic field. Since the impact plasma cloud is partially ionized, the interaction of the solar wind with an expanding impact plasma cloud will initially resemble that between the solar wind and a planetary ionosphere. In particular, an MHD bow shock wave will develop ahead of the expanding cloud. Within the shocked layer, the field is amplified while outside the shock wave, the plasma and field environment is unperturbed. In order to determine the bow shock structure and shape, we have taken the approach of scaling the numerical gasdynamic results of Spreiter and Stahara[4] for the Earth's bow shock with $M_s = 8$ and $\gamma = 5/3$, where γ is the usual ratio of specific heats. The outer dashed line in each plot of the Figure indicates the scaled location of the bow shock upstream of the impact plasma cloud at different times after the impact. In order to calculate the magnetic field change with time behind the bow shock wave, we have adopted a kinematic procedure in which the magnetic field exerts no influence on the solar wind flow past the impact plasma cloud. The incident magnetic field is assumed to be in the plane of the bow wave as shown in the Figure and to have an upstream magnitude of B_∞. Induced fields in the lunar interior were neglected in this initial calculation. The resulting magnetic field lines are plotted in the Figure. As the bow shocks converge in the antipodal zone, the above procedure becomes invalid and the magnetic field amplitude is simply estimated from conservation of flux. No provision for the (likely) occurrence of plasma instabilities, reconnection of magnetic fields, etc. at the antipode has yet been made in these calculations. In any case, the results show a substantial magnetic field amplification at the basin antipode as the impact plasma converges approximately 400 seconds after the simulated impact.

Remanence Acquisition Mechanisms: The time scale for expansion of the impact plasma cloud to the antipode as deduced from the hydrocode calculations described above is of the order of 400 to 500 seconds for impact velocities of 15 to 20 km/s. This time scale has important implications for the mechanism responsible for remanence acquisition in the antipodal zone during the period of compressed field amplification. Since magnetization must occur within a relatively short time interval, the main candidate mechanisms are: (1) Acquisition of shock or rapid thermal remanence resulting from compressive stresses generated by converging seismic waves at the antipode; and (2) acquisition of shock or rapid thermal remanence by impact of solid ejected secondaries from the basin forming event. In the case of mechanism (2), ballistic calculations on a spherical Moon for ejection angles of 30° to 60° yield antipodal arrival times of 28-50 minutes (1700-3000 seconds)[5]. In the case of mechanism (1), arrival times of seismic body waves with mantle velocities of $\sim$ 8 km/s are about 8 minutes (480 seconds). Thus on the basis of time scale alone, convergence of seismic body waves appears to be the most likely candidate for effecting the magnetization of near-surface materials during the period of compressed magnetic field amplification by the impact plasma cloud.

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