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Spontaneous magnetic field generation in hypervelocity impacts

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Abstract—At sufficiently high impact velocities, plasma clouds are generated in the early stages of hypervelocity impacts. Electrical currents and their associated magnetic fields can be generated in such clouds by several well-known mechanisms. For example, nonaligned temperature and electron density gradients resulting from chemically layered targets will produce a dipolar magnetic field in the plasma cloud. Such fields have durations from 10^{-6} sec to a minute or so, depending upon the size and energy of the event. The generated field strength will lie between the local ambient value and the plasma pressure limit, say 100 Teslas (10^{11} γ) for central pressures of 10 Mbar. Such enormous field strengths have been observed in laser-target experiments, where the specific power densities are like those of a 10–20 km sec^{-1} impact. Both shock remanence (SRM) and thermoremanence (TRM) could be acquired by ejecta and nearby rock as this material moves through or is processed in the local field.

INTRODUCTION

REMANENT MAGNETISM IN LUNAR SAMPLES and the presence of permanent lunar magnetic anomalies strongly argue that at least the outer portion of the moon was magnetized early in lunar history. The origin of the magnetizing field is unknown. Theories of its origin fall broadly into two groups: internal origins, such as core dynamos (Runcorn *et al.*, 1970), primordial magnetization of the lunar interior (Runcorn and Urey, 1973; Strangway and Sharpe, 1974), and local subsurface dynamos (Murthy and Banerjee, 1973); and external origins such as impact events (Hide, 1972; Gold and Soter, 1976) and thermoelectric effects in lava basins (Dyal *et al.*, 1977). Measurements of the global lunar magnetic dipole moment (Russell *et al.*, 1974) are insufficient to tightly constrain these theories (Srnka, 1976), but if the lunar paleointensity measurements which give ancient fields on the order of 1 Oe are correct, then the primordial magnetization theory can probably be ruled out (Stephenson *et al.*, 1976). This paper examines some electromagnetic and plasma processes which should occur in a hypervelocity impact, and suggests that such an event may magnetize solid material in and near the impact.

Recent data (Banerjee and Swits, 1975; Banerjee and Mellema, 1976; Banerjee, 1976) on the magnetization of several samples from the Apollo 17 Station 2 Boulder 1 at the Taurus-Littrow region of the moon suggest that a secondary magnetization was imprinted in the samples during the low-temperature (~450°C) assembly of this breccia boulder, overprinting the more stable high-temperature magnetization acquired by the mineral and lithic fragments during their original formation. Such evidence points to an impact origin for the secondary magnetization. Other evidence which suggests that impacts have played a central role in determining lunar magnetization is the similarity in scale sizes between lunar surface magnetic anomalies and craters (Lin *et al.*, 1976), and the laboratory observations of shock remanent magnetization in pressure regimes similar to those expected in the outer regions of impact craters. On the other hand, since only one lunar crater (Van de Graaff) is known to have a strong magnetic anomaly associated with its structure, this relationship is by no means established.

Although not enough is known about the magnetic effects of hypervelocity impact, it is now established that remanence can be acquired through shock if a magnetic field is present (Cisowski *et al.*, 1975, 1976). If local lunar magnetic fields can be amplified during an impact to the 10^3–10^5 γ levels ($1\gamma = 10^{-9}\,T$) indicated by the range of paleointensity work, as first suggested by Hide (1972), or perhaps generated during the event by plasma or other processes, then the role of shock remanent magnetization (SRM) in lunar magnetism would be clearer. The importance of cratering as a planetary process provides the motivation for the study of such "exotic" mechanisms.

It is proposed here that hypervelocity impacts of meteoroids and larger objects onto early planetary surfaces can generate large, short-lived magnetic fields as a result of their high specific power densities (10^{15}–$10^{17}\,Wm^{-2}$), plasma production in their ejecta clouds, and the likely vertical and possibly horizontal chemical inhomogeneity of the target surfaces on scales comparable with the crater dimensions. This discussion is at best semi-quantitative, and is intended to encourage those with large computational cratering codes and others with experimental facilities to search for the magnetic fields discussed below.

THEORY

Most hypervelocity impacts on planetary surfaces should produce some plasma in their ejecta clouds. Wetherill (1976) has argued that the late stage of accretion of the moon was characterized by mean impact velocities of at least 8 km/sec, with some velocities above 10 km/sec. The mean velocities for the late heavy bombardment around 4.0 b.y. ago and for more recent events may have been even higher, say 20 km/sec (Wetherill, 1975; Dohnanyi, 1972). Laboratory experiments with micrometeoroid impacts at such velocities show that 10^{-4}–10^{-2} of the projectile mass is ionized during the early stages of the impact in this velocity range (Dietzel *et al.*, 1972). Even with the addition of gas and dust from the target material this partly ionized ejecta cloud will be electrically conducting (Alfvén, 1963). If the plasma cloud is defined as that volume within which the ionization equals 1% or more numerically, this region can be studied from a magnetohydrodynamic (MHD) standpoint on a large scale, or by the plasma approach for smaller scale processes.

(a) *General considerations*

A simple theoretical model for the development of electrical currents and their magnetic fields in the expanding plasma cloud is constructed by combining the generalized Ohm's law for a low-temperature plasma with Faraday's law of induction. Neglecting pressure gradients due to radiation, and assuming that the ion mobility is much less than the electron mobility in the plasma, the change of magnetic induction **B** is then given by:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\mathbf{V} \times \mathbf{B} - \frac{1}{\mu\sigma}\nabla \times \mathbf{B} - \frac{1}{\mu e n}(\nabla \times \mathbf{B}) \times \mathbf{B}\right] + \mathbf{S}, \tag{1}$$

where

$$\mathbf{S} = \nabla \times \left[\frac{k}{en}\nabla(nT) - \boldsymbol{\alpha} \cdot \nabla T\right], \tag{2}$$

is the source term. Here **V** is the velocity of the bulk plasma motion in the reference frame where **B** is measured, e is the electron charge, k is Boltzmann's constant, n and T are the plasma electron number density and temperature, $\boldsymbol{\alpha}$ is the plasma tensor thermoelectric coefficient, and μ and σ are the magnetic permeability and electrical conductivity of the plasma, respectively. These equations apply under the assumptions made above provided the time scale for a change in **B** is much larger than an electron gyro period τ_e ($\tau_e = 2\pi m_e/eB$, where $B \equiv |\mathbf{B}|$ and m_e is the electron rest mass). At $B = 1\,\mathrm{G}$ ($10^5\,\gamma$), $\tau_e = 3.6 \times 10^{-7}$ sec.

The first term on the right hand side (r.h.s.) of Eq. (1) describes the convective changes in **B** due to bulk motion of the plasma, such as compression of an ambient magnetic field by the explosion. The second term on the r.h.s. describes the diffusion of **B** through the electrical conductivity of the cloud. The third term is the Hall effect. The values of n, T, **V**, and **B** determine which terms dominate. The source term **S** describes the growth of electrical currents due to pressure gradients, called drift currents, plus the currents due to thermoelectric (Seebeck and Thompson) effects caused by temperature and chemical inhomogeneities. For the purposes of this discussion, only the drift currents will be considered. Then to first approximation Eq. (2) gives:

$$\mathbf{S} = \frac{k}{e}\nabla \times \left(\frac{T}{n}\nabla n\right) \tag{3a}$$

or if n has a spatial variation in primarily one coordinate,

$$\mathbf{S} \cong \frac{k}{en}\nabla T \times \nabla n. \tag{3b}$$

The physical interpretation of Eq. (3b) is straightforward. Assume that the initial field $\mathbf{B}_0$ is zero, or so small that the electron gyro radii are larger than the plasma cloud dimensions so that the electrons move in essentially straight lines. Then if ∇T and ∇n are not aligned (e.g., due to strong chemical gradients in the target), reservoirs of high electron density exist along isotherms which intersect lower density regions. Such anisotropic pressure distributions are thermally unstable, and the high density regions "fill" the low density areas by electron mass motion. Since the ions are much less mobile, this net motion produces a current in the $-\nabla n$ direction. If ∇T and ∇n are separately maintained, the current will continue to increase until its associated magnetic field inhibits the electron motion by finite gyro radius effects. When finally $\partial \mathbf{B}/\partial t = 0$, the quasi-static pressure gradient $\nabla(nkT)$ will be opposed by a magnetic field gradient, and such a system is then in MHD equilibrium.

(b) *Time scales*

If a hypervelocity impact deposits enough kinetic energy onto a chemically inhomogeneous target in a short enough time, a plasma cloud containing such inhomogeneities will be produced in the early stages of the ejecta motion. The existence of spontaneous magnetic fields in these circumstances seems reasonable, but their magnitudes are very uncertain. To a large extent the field strength is controlled by the ratio of the generation time for **B** to the diffusion and convection time scales.

The kinetic energy of the projectile is deposited in the target within a time τ_E given roughly by

$$\tau_E \approx \frac{R}{V_p} \cdot \left[1 + \left(\frac{\rho_p}{\rho_0}\right)^{1/2}\right],$$

where R is the projectile size, V_p is its impact velocity, and ρ_p and ρ_0 are the initial mass densities of the projectile and target, respectively (see Pirri, 1977 and the references therein). Reasonable density ratios then give $\tau_E \lesssim 5R/V_p$, or $\tau_E \approx 1$ msec for a 1 m radius object and $V_p = 10$ km/sec. This is very long compared with typical ionization times of 10^{-9} sec or less at 5–10,000°K and solid-state densities characteristic of the central fireball region in a hypervelocity impact (Drapatz and Michel, 1974). Thus plasma and magnetic field will be generated as the projectile is decelerated in the target material and then explodes.

Two time scales govern the decay of **B** as the cloud expands: the first is the convective transport time L/V given by the cloud size divided by the plasma velocity; the second is the magnetic diffusion time or "Cowling" time τ_D given by $\mu\sigma L^2/\pi^2$ for a spherical cloud. Since $R \ll L$ and $V \gtrsim V_p$ (Eichhorn, 1976), spontaneous fields can be built up faster than they are lost by diffusion if $\tau_D \gg \tau_E$ or

$$\mu\sigma V_p L \gg 5\pi^2.$$

Even at the low temperatures observed in ejecta plasma clouds in laboratory studies (2500–5000°K or 0.2–0.4 eV; Eichhorn, 1976) and the high number densities expected (say 10^{21} m^{-3} or more), the plasma electrical conductivity σ should exceed 100 $(\Omega\text{-m})^{-1}$. Taking $V_p = 10$ km/sec and $\mu = \mu_0$ requires $L \gtrsim$ 100 m which should be characteristic of ejecta clouds produced by meter-sized projectiles. Much larger impacts with $L > 100$ km or more would have $\tau_D \approx$

10^5 sec and $L/V \approx 5$–10 sec, so that diffusion is less important than mass motion for events which form kilometer-sized craters. Extension of this simple argument to basin-forming events gives the duration of any spontaneously generated magnetic fields as minutes or more, depending upon the details of the impact and the plasma cloud.

(c) *An example*

Consider an impact with $\tau_E \ll \tau_D \lesssim L/V$. Then the peak generated **B** as given from Eq. (3b) is

$$\mathbf{B}_{\max} \approx \int_0^{\tau_E} \frac{k}{en} \nabla T \times \nabla n \, dt. \tag{4}$$

To a first approximation the expanding impact cavity is hemispherical, and a spherical polar coordinate system is used. If $T = T(r)$ alone and $n = n(r, \theta, \varphi)$, where θ is the polar coordinate and φ is the azimuthal coordinate, then

$$\nabla T \times \nabla n = \frac{1}{r} \cdot \frac{\partial T}{\partial r}\left(\frac{\partial n}{\partial \theta}\hat{\varphi} - \frac{1}{\sin\theta}\frac{\partial n}{\partial \varphi}\hat{\theta}\right).$$

A first-order, *linear* approximation to $\mathbf{B}_{\max}$ in this case is then given by Eq. (4) using $\tau_E = 5R/V_p$,

$$\mathbf{B}_{\max} \approx \frac{5kR}{en V_p r}\left(\frac{\partial T}{\partial r}\right)\left(\frac{\partial n}{\partial \theta}\hat{\varphi} - \frac{1}{\sin\theta}\frac{\partial n}{\partial \varphi}\hat{\theta}\right).$$

The magnitude of this time-averaged vector quantity at $r = R$ when $t \approx \tau_E$ is thus roughly

$$|\mathbf{B}_{\max}|_R \equiv B_R \approx 60\left[\frac{\partial T}{\partial r} \cdot \frac{\Delta n}{n}\right]_R \qquad \text{(in gamma)},$$

where no compression of the magnetic field has been considered. The radial temperature gradient and the electron density fluctuation ($\Delta n/n$) at the edge of this expanding plasma cloud are estimated as $\partial T/\partial r \geq 10°\text{K/m}$ from the work of Stöffler (1971) on the Ries event, and $10^{-2} \lesssim \Delta n/n \lesssim 10^2$ depending upon the initial large-scale chemical inhomogeneity of the target material. For example, if the target is vertically stratified with say a 10% increase in mean atomic number between successive layers, and if the cavity excavates more than two successive layers, one might expect $\Delta n/n \approx 0.1$ and thus $50 \lesssim B_R \lesssim 100\gamma$. Although these fields are small, it should be remembered that a simple linear estimate is used here, and field compression has been ignored. Non-linear plasma processes and thermal instabilities (Tidman and Shanny, 1974) may amplify these fields considerably. Theoretical work is in progress to study such effects. The magnetic field configuration for $t > \tau_E$ in such an event is depicted in Fig. 1. The induced currents **j** parallel regions of differing electron density, and their magnetic fields balance the plasma pressure differences across such boundaries. Here the magnetic moment vector of the plasma cloud is perpendicular to the surface. For

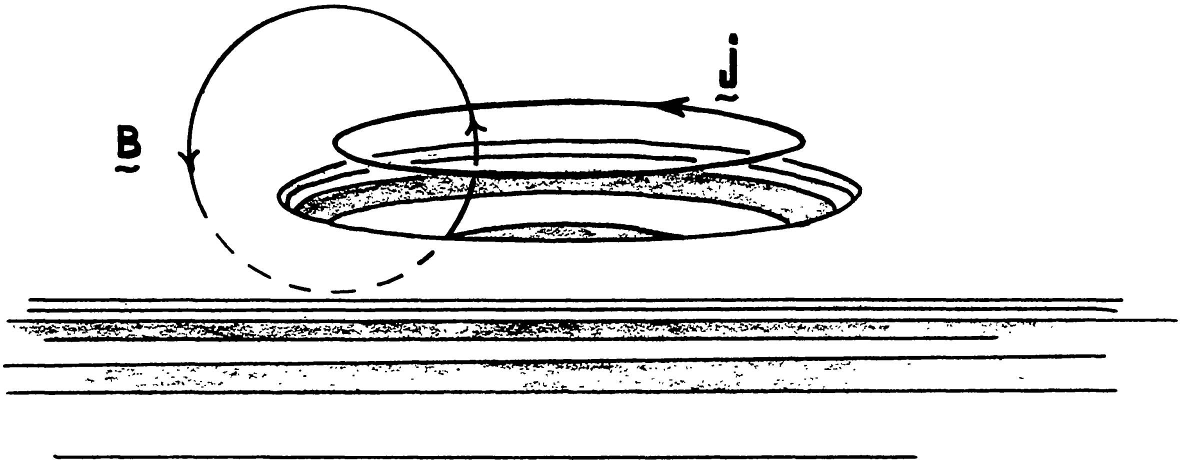

Fig. 1. Conceptual view of one component of the current and magnetic field systems generated in a hypervelocity impact due to a vertically stratified target surface.

an impact onto a laterally inhomogeneous target, this moment vector is in the plane of the surface. The simple geometry shown would of course be highly modified in a real event when magnetic field compression and bulk plasma motions occur.

DISCUSSION

Although magnetic field generation has not yet been observed in impact experiments, spontaneous fields have been observed in several laser–target interaction experiments (Stamper *et al.*, 1971; Bird *et al.*, 1973; Stamper and Ripin, 1975). The physical processes of ionization and plasma heating in laser experiments differ somewhat from those expected in hypervelocity impacts, but there are numerous similarities (Pirri, 1977). For example, chemical inhomogeneities as magnetic field sources have been studied in the laser situation (Tidman, 1974), and the collisional MHD and plasma scaling laws suggest that similar effects will be observed if the specific powers on the targets are equal (Beiser and Raab, 1961). For a projectile of density ρ the average impact power over the time τ_E is on the order of ρV_p^3, or 10^{15}–5×10^{16} Wm^{-2} for $2.0 \leq \rho \leq 6.0$ g cm^{-3} and $8 \leq V_p \leq 20$ km/sec. Laser–target experiments in this same power range produce magnetic fields of 100–1000 G (10^7–10^8 γ) a few crater diameters from the focal spot, with field durations governed by the plasma expansion time. In general terms, these local magnetic fields must lie in the range $2B_0 \leq |\mathbf{B}| \leq (2\mu nkT)^{1/2}$ where B_0 is the initial ambient magnetic field value (Price, 1974; Widner, 1973); the lower limit is given by the compression of the ambient field. The upper limit is determined by balancing the induced magnetic field pressure against the particle pressure, and is on the order of 10^{10}–10^{11} γ for solid-state densities and $T = 10^4$°K. Such enormous fields can be produced, and have been observed, if energy is deliberately deposited in the plasma cloud rather than the solid target (Stamper and Ripin, 1975).

These theoretical arguments and some tantalizing results from laser experiments in the appropriate power range suggest that significant but short-lived magnetic fields could be generated in energetic, high power impacts. A discussion of the applicable magnetic remanence mechanisms which would record such fields in the crusts of planetary bodies is equally as speculative, and no attempt is made here to explore the difficult remanence problem in detail. However, two mechanisms come immediately to mind: SRM and TRM. Shock remanence will be acquired in those objects, and in that material near the impact point, in which the pressure rises to 20–100 kbar as the shock wave passes by in the presence of the spontaneous magnetic field. Thermoremnance would be acquired by that ejecta which cools faster than the decay of the field (e.g., very small fragments in the ejecta plume which are heated to a large fraction of or just above their Curie points and radiatively cool in flight), or by the material near the impact which is rapidly heated and cooled by the successive passages of the shock and rarefaction waves. A consequence of such a model is the prediction of strong magnetization in breccias, with individual lithic fragments showing different intensities and directions of magnetizations. A severe difficulty with such in-flight magnetization is that the assembled breccia layer should show no net magnetization, and hence the lunar surface magnetic anomalies remain unexplained if only this mechanism is invoked. Shock magnetization of emplaced cool materials removes this difficulty, but at the same time requires the presence of spontaneous magnetic fields up to 1 Oe in magnitude at large distances from the impact point.

It is possible that more than one source of magnetic field and more than one remanence mechanism is responsible for the magnetization of the moon. If spontaneous magnetic field generation is a natural consequence of hypervelocity impacts on inhomogeneous targets, maps of magnetic anomalies such as those on the moon may provide additional information on the energetics of the cratering bodies and on the state of the early crust.

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