Shock wave, a possible source of magnetic fields?

B. A. Ivanov¹, B. A. Okuletsky², and A. T. Basilevsky³

USSR Academy of Science, Moscow

Abstract—One possible effect due to impact cratering is the transformation of part of the kinetic energy of the projectile to energy in the electromagnetic field. Shock-induced polarization of piezo- and dielectric material could be the mechanism by which this is accomplished. Although the estimates show that the fraction of kinetic energy transformed by this mechanism is rather small, the effect could be sufficient to form some magnetic features of planets that have even a slight planetary magnetic field of their own. The possible limits of this effect are still uncertain. The mechanism suggested is attractive because it gives a possible explanation for the high values of remanent magnetization displayed by some lunar samples, without calling for the hypothesis of a strong global magnetism for the moon in the past epochs.

CRATERING IS the most prominent but probably not the most interesting effect of impacts or explosions. Other physical and chemical processes are also induced by shock waves. Results of these processes should be found during investigations of planets that have impact-cratered surfaces.

Several effects due to shock wave are well known, such as shock metamorphism, shock melting, chemical differentiation in impactites, etc. (see for example Dence, 1971; Masaytis et al., 1975; Parfenova and Yakovlev, 1976). One more possible effect due to impact cratering is the transformation of part of the kinetic energy of the projectile to electromagnetic energy. The possibility of the latter transformation was first recognized during the analysis of the magnetic profiling data taken by Lunokhod-2 at Le Monier area (Ivanov et al., 1976).

Lunokhod-2 profiling revealed quasin sinusoidal magnetic anomalies associated with impact craters with impact diameters 50–400 m (see Fig. 1). These anomalies represent the quasin sinusoidal variations of magnetic field intensity around the certain level which is the local background. In searching for the mechanism of formation of these anomalies the suggestion was made that crater excavation and anomaly induction are both caused by the same phenomenon—shock wave propagation, as the result of a magnetic field impulse produced by shock-induced electric polarization in the target rocks.

Shock-induced polarization can be considered as an electric current flowing through the shock wave front. This current is capable of causing some magnetic effects on adjacent materials. When a shock wave is passing through materials containing shock-polarized and ferromagnetic components, the induced ele-

¹Schmidt Institute of Physics of the Earth.
²Shirshov Institute of Oceanology.
³Vernadsky Institute of Geochemistry and Analytical Chemistry.
Fig. 1. Typical shape of magnetic anomaly across the crater. Lunokhod-2 measurements, bottom of Le Monier, March 16, 1973. $H_x$—horizontal component of magnetic field, $H_z$—vertical one.

tromagnetic field could be fixed by the ferromagnetic components. It may also be preceded or followed by direct shock effects on ferromagnetic components.

Lunar rocks consist of plagioclase, pyroxene, and olivine and other minerals. Between these components silica minerals occur. It is known that plagioclase, pyroxene, and olivine are dielectrics and silica minerals are piezoelectrics. Under the shock wave propagation shock-polarization occurs in piezoelectric (Graham et al., 1965) as well as in some dielectric materials (Hawer, 1965; Mineev et al., 1968). A review of theoretical and experimental works in this field can be found in Mineev et al. (1976). The ferromagnetic component of lunar rocks is represented mainly by Fe-metal at abundance up to 0.1% (Fuller, 1974). This content is sufficient to produce the observed local magnetic anomalies of the Moon (Guskova et al., 1974).

This mechanism allows the evaluation of the amplitude and geometry of the magnetic field induced during the propagation of a semispherical shock wave into the semisphere occupied by shock polarized dielectric. Experimental data show that shock compression of polycrystalline rocks induces polarization in the direction normal to the shock wave front (Mineev et al., 1968). To simplify the evaluation let us suppose, as a first approximation, that the shock wave generates in a unit of volume a dipole momentum $P$ and that the time of relaxation of this polarization is infinitely large (i.e., the current of depolarization
is negligible). A more accurate estimation needs additional information on target mineralogy and character of the polarization mechanism. The assumption used is rather correctly applicable if a width of polarized zone is comparable to shock wave radius.

Let us consider a volume

\[ dV = R^2 \sin \theta \, d\theta \, d\rho \, dR \]  

(1)
in spheric coordinates. The shock wave front passes through this volume during the time

\[ dt = \frac{dR}{D}, \]  

(2)
if the shock front has a hemispheric shape, and \( D \) is a velocity of this front. After the shock wave has passed, rocks in the volume (1) have been polarized and the value of its dipole momentum is

\[ d\mathcal{P} = P(R) \, dV \]  

(3)
directed normal to the front surface (\( P(R) = \) specific density of charge, coulomb/cm\(^2\) in cgs).

Then, according to (1) and (2), the rate of changing in time is

\[ \frac{d\mathcal{P}}{dt} = PDR^2 \sin \theta \, d\theta \, d\rho. \]  

(4)
The derivative \( d\mathcal{P}/dt \) have the meaning of an electric current through the shock front per unit of the shock front surface.

Let us consider a value and direction of magnetic field, generated by polarization current (4) between points \( A_0 \) at \((R, \theta, \rho)\) (see Fig. 2) and \( A_1 \) at \((r, \theta, 0)\). According to Landau and Lipshitz (1967) this field is determined as

\[ dH = DP \left[ \frac{R}{|R|} \times \text{grad} \frac{1}{\delta} \right] R^2 \sin \theta \, d\theta \, d\rho \]  

(5)
where \( \delta \) is a vector which connects the points \( A_0 \) and \( A_1 \).

Supposing that \( D \) and \( P \) are constant at any point of the shock front surface, then at any given moment of the time we can integrate (5) throughout the front surface:

\[ H_y = DPI(R, A), \]

\[ H_x = H_z = 0, \]  

(6)
where \( H_x, H_y, \) and \( H_z \)—are components of magnetic field at \( A_1 \) and

\[ \text{I}(R, A_1) = \int_0^{2\pi} d\rho \int_0^{\pi/2} d\theta R^2 \sin \theta \frac{z \cos \rho \sin \theta - x \cos \theta}{[x^2 + z^2 + R^2 - 2R(x \sin \theta \cos \rho + z \cos \theta)]^{3/2}}. \]  

(7)
(\( x \) and \( z \) are coordinates of \( A_1 \) point, \( y = 0 \)), i.e., \( \text{I}(R, A) \) is a function of mutual position of shock wave and point of measurements.
Let us designate

\[ H_0 = DP. \]  

(8)

\( H_0 \) has the dimension of the intensity of magnetic field. If the units of \( D \) are \( \text{km/s} \) and the units of \( P \) are \( \text{coulomb/cm}^2 \) then

\[ H_0 = 0.4\pi \times 10^5 PD \text{ (oersted)}. \]  

(9)

For \( D = 8 \text{ km/s} \) and \( P = 10^{-9} \text{coulomb/cm}^2 \)

\[ H_0 = 10^{-3} \text{Oe} = 100\gamma, \]  

(10)

(we used the \( P \) value for enstatite from Mineev et al., 1968). The \( P \) value is very high for quartz (Gracham et al., 1965) but its polarization depends on the orientation of the crystal axes. The total \( H \) then depends on the percentage of quartz in the rocks.
The geometric factor $I(R_1A_1)$ in (6) can be estimated for a crater of conical shape with ratio diameter/depth = 8 (see Fig. 3) and for a moment of time when the shock wave radius equals 0.6 depth. $I(R_1A_1)$ for this case is shown on Fig. 3 for $A_1$ points placed on the level of future crater profile. Then the maximum magnetic intensity consists of about $0.5H_0$ and is achieved at a distance as large as the shock wave radius from the center. If one assumes that ferromagnetic components of rocks beneath the crater bottom were magnetized by this field and that they kept some part of the remanent magnetization (in proportion to the amplitude of the influencing field) the geometry of the horizontal component of the magnetic field across the crater is shown on Fig. 3. Comparing Fig. 1 and Fig. 3 shows the qualitative agreement between the calculated impact-induced anomalies and the magnetic anomalies revealed by Lunokhod-2, some craters in Le Monier area. Comparing these figures one can take into account the presence of the background at natural phenomena and the absence of it at calculated model.

![Fig. 3. Calculated shape of magnetic field: (a) calculated character of magnetic field in the bottom of future crater at the moment of time when radius of shock wave front is equal to 0.6 crater depth; (b) geometry of lines of equal intensity of magnetic field at the same moment of time: 1—position of shock-wave front, 2—bottom of future crater; vector of magnetic intensity is directed normal to the plane of the figure. To make this figure more obvious crater radius is adopted as large as 200 m.](image-url)
This agreement probably indicates that the near-crater magnetic anomalies observed by Lunokhod-2 were produced by the above described mechanism of shock-induced polarization. The possible limits of this effect are now uncertain.

The possibility of formation by this mechanism of the magnetic anomalies associated with large craters is actually determined by the time of depolarization of rocks after the shock wave. If this time is rather small the effect of shock wave polarization would be localized on inhomogeneities in the rock massif and would be negligibly small at the distance as large as one crater diameter. Because of this circumstance the application of this effect to large impact craters and basins is unclear. The relations between the remanent magnetization of returned lunar samples and proposed mechanism are still not clearly understood. To resolve this problem the experimental simulation is now in progress.

If this mechanism of rock magnetization was indeed realized on the moon and other planets, its role should be much more large in the epoch of intense bombardment. We suppose that at any given impact event the percentage of intensely magnetized target rocks is probably rather small but at epoch of intense bombardment the high frequency of impacts could result in rather large cumulative percentage of intensely magnetized samples. If this mechanism is real then intensely magnetized samples should be found between young impacts of the moon also. It is interesting to note that the highest remanent magnetization is characteristic for the very lunar rocks which were formed

\[ 10^{-5} \leq J \leq 10^{-4} \]

Sample age, b.y.

Fig. 4. Stable remanent magnetization of lunar samples vs. their absolute age. According to Okullessky (1976).
during this intense-bombardment epoch (Fuller, 1974; Okulessky, 1976); see Fig. 4. Simple estimations show that the fraction of kinetic energy transformed by this mechanism into electromagnetic energy is rather small and therefore the effect could be sufficient to form some magnetic features only on planets that have slight proper planetary magnetic field.

Acknowledgments—The authors are indebted to L. G. Bolkhovitinov for prompting them on the idea on magnetic effect of shock polarization. Authors also thank L. L. Vanjan and E. A. Eroshenko for fruitful discussions. Sincere thanks to L. B. Ronca from Wayne State University, Detroit, U.S.A., for editing the text.

REFERENCES