Deep Electromagnetic Sounding of the Moon With Lunokhod 2 Data

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Fluctuations of the frozen-in magnetic field in the solar plasma induce electric currents in the conducting interior of the Moon. The magnetic field of these currents is too weak to overcome the dynamic force of the solar wind and form a shock wave ahead of the Moon. It diffuses into the solar plasma, dying away exponentially as $\exp(-\omega_0 Z/c)$, where ω_0 is the electron plasma frequency; c is the speed of light; and Z is the distance from the surface of the Moon. As is evident, the depth of penetration of the field depends only on the density of the plasma, and it usually is a few kilometers. In comparison with the depth of penetration of fluctuations of the magnetic field into the material of the Moon, measured in hundreds of kilometers, it can be considered that the Moon is surrounded by an ideal conductor on the illuminated side. Therefore, on the illuminated side, the induced magnetic field turns out to be compressed between the conducting interior of the Moon and the solar plasma, which leads to a severalfold increase in its intensity.

On the other hand, on the darkside of the Moon a cavity forms with a very low plasma density, where the induced magnetic field propagates as in a vacuum. On the lateral surfaces of the cavity and on the illuminated side of the Moon, as in an ideal conductor, the normal component of the induced magnetic field reverts to zero: $H_{ni} = 0$. Consequently, the vertical component on the illuminated side of the lunar surface reflects the behavior of the external field and does not depend on the structure of the Moon (ref. 1).

Let us consider a two-layer model of the Moon in which the outer layer, in conformance with measurements of electrical conductivity of samples, is assumed to be an insulator, and the inner one, with radius a, is assigned a spherical impedance $Z(\omega,n)$. Then, in the region formed by the outer layer of the Moon and the cavity, the magnetic field intensity satisfies the wave equation and propagates with the speed of light. Since the length of the lunar cavity is not over 3×10^3 km, the delay time is measured in hundredths of a second and can be disregarded for fluctuations having periods of tens of seconds. Consequently, in the region being examined the wave equation is converted into a Laplace equation, with the following boundary conditions:

$$H_n = H_{ne} + H_{ni} = H_{ne}$$

where H_e is the frozen-in magnetic field moving past the Moon, with a velocity equal to or exceeding the velocity of the solar wind. Although fluctuations of the interplanetary magnetic field can arbitrarily change with time, it is convenient to examine the problem for a time-harmonic of the type $\exp(-i\omega t)$.

If a solution of the Laplace equation is sought in the form of an expansion by spherical harmonics, we have for their amplitudes $h_r = h_{re}$ on the surface separating the Moon from the solar plasma, and

$$\frac{h_r}{h_\theta} = \frac{n(n+1)\, Z\,(\omega,n)}{-i\omega\mu a}$$

on the surface of the inner conducting sphere. Here, h_r is the spatial amplitude of the radial variations; h_θ is the meridional magnetic variation; n is the number of spherical harmonics; and $Z(\omega,n)$ is the impedance of the inner sphere (ref. 2).

A numerical solution of the formulated problem (ref. 3) allows the following conclusions to be made:

1. If the wavelength of the exciting field exceeds 15×10^3 km, it can be considered, with satisfactory accuracy, that it changes cophasally everywhere.

2. On the illuminated side around the subsolar point, there is a region where the magnetic field depends slightly on the length of the lunar cavity.

Consequently, keeping in mind the observations on the illuminated side, a simplified model can be used in which the time of propagation of the solar wind past the Moon is disregarded.

The induced magnetic field carries information on the deep electrical conductivity of the Moon. There are two basic methods for extracting this information. The first method is study of the impedance, i.e., the ratio of the components of the electrical and magnetic fluctuations tangential to the lunar surface. Although this is widely used under terrestrial conditions, it has not yet been used on the Moon because of technical difficulties.

In the second method, one uses the ratio of the horizontal magnetic component on the lunar surface to its unperturbed value, as measured by a satellite of the Moon. As shown by experiment (ref. 1), the horizontal magnetic field increases threefold to fivefold in the harmonic mode for fluctuation periods of about 20 to 30 s, and drops to 1 for periods of about an hour. This drop reflects gradual penetration of the electromagnetic field into the interior of the Moon. If the interplanetary magnetic field changes by steps, a similar process is observed where the induced currents practically completely decay and the magnetic gain approaches unity a few minutes after arrival of the step change at the Moon.

Discontinuities propagating from the Sun have one important characteristic: the magnetic field in them usually is linearly polarized. This makes it possible to use the ratio of the horizontal and vertical magnetic components on the surface of the Moon, normalizing it to unity for $t \to \infty$. This procedure was used in analysis of a number of magnetic pulses recorded by the Lunokhod 2 magnetometer. An example of the meridional and vertical components of a magnetic field pulse, recorded at 0 hours 31 min 35 s on 23 March 1973, is shown in figure 1. The vertical component has the form of a trapezoid, which approaches a steady value in approximately 16 s. The horizontal component initially increases sharply, then decreases, and after 3 min it also settles at a constant level.

The pulse of 23 March was recorded at a solar wind velocity over 730 km/s, according to the data from the Prognoz and Pioneer 9 satellites. This means that for a Fourier harmonic with a period exceeding 20 s, the effect of the finite time of passage of the solar wind past the Moon on the electromagnetic induction can be disregarded.
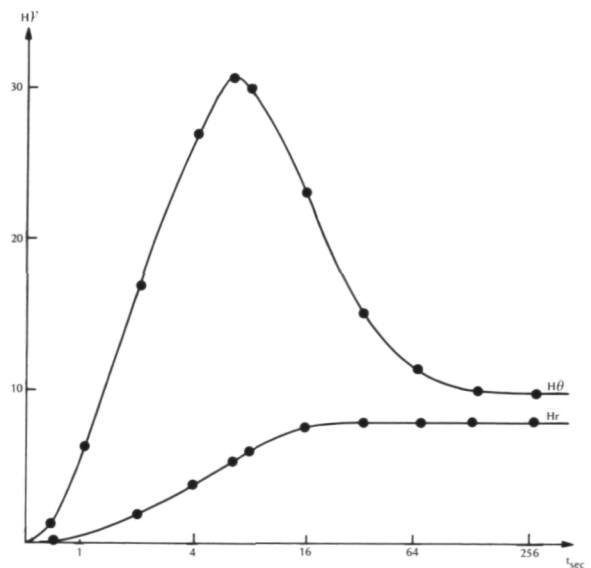
If a change in the vertical component re-

Figure 1.—*Meridional and vertical components of unsettled magnetic field, from Lunokhod 2 data.*

flecting the behavior of the induced field had the form of an ideal rectangular step, the transitional characteristic of the Moon could be determined from the ratio $H_\theta(t)/H_\theta(\infty)$. However, the impulse of the vertical component differs significantly from a rectangular step. To allow for the shape of the pulse H_r, it is convenient to change to spectra; for example, to use the Laplace transform

$$h(p) = \int_0^\infty H(t) \, e^{-pt}dt.$$

In this case, instead of $H_\theta(t)/H_\theta(\infty)$, we have:

$$\tilde{h}(p) = \frac{h_\theta(p)}{h_\theta(o)} : \frac{h_r(p)}{h_r(o)}$$

The increase in the tangential magnetic field was determined in the interval 5×10^{-3} s$^{-1} \le p \le 2$ s^{-1}. It contains all the information on the deep electrical conductivity of the Moon which there was in the pulse being analyzed.

However, before attempting to extract this information, we must consider the effect of the lunar cavity. This effect differs at different points on the surface of the Moon; therefore, it is convenient to introduce corrections that take the symmetry of the cavity into consideration. Calculations have shown that for the point at which the pulse being analyzed was recorded, the observed gain decreases to 1.5 times that of a symmetric model when the solar plasma surrounds the Moon on all sides.

$\tilde{h}_{asym}$	$\tilde{h}_{sym}$	$\dfrac{\tilde{h}_{sym}}{\tilde{h}_{asym}}$
2.7	3.9	1.5
2.2	2.6	1.2
1.7	1.9	1.1
1.4	1.4	1.0

From the corrected values of the gain, the apparent resistivity $\rho_a = 9.5 \times 10^5 p/\tilde{h}^2(p)$ was calculated. It is a convenient form for presenting the sounding results (ref. 4). The values of the apparent resistivity are shown by black dots in figure 2, as a function of the parameter $p^{-1/2}$, which characterizes the depth of penetration of the field into the Moon. It must be noted that at $p^{-1/2} > 10$,

the apparent resistivity stops reflecting the change in conductivity with depth and approaches an asymptote, characterizing decay of the currents induced in the Moon.

For interpretation of the experimental graph of the apparent resistivity, a series of theoretical curves was calculated for the following parameters:

Model 1. $\rho_1 > 10^8$ ohm·m $d_1 = 100$ km
           $\rho_2 = 10^4$ $d_2 = 800$
           $\rho_3 = 10^2$

Model 2. $\rho_1 > 10^8$ $d_1 = 250$
           $\rho_2 = 10^4$ $d_2 = 800$
           $\rho_3 = 10^3$

Model 3. $\rho_1 > 10^8$ $d_1 = 180$
           $\rho_2 = 10^4$ $d_2 = 300$
           $\rho_3 = 10^5$ $d_3 = 300$
           $\rho_4 = 10^3$

Model 3 demonstrates the best agreement with experimental data, which support the existence of a layer having increased conductivity in the 200- to 500-km-depth interval
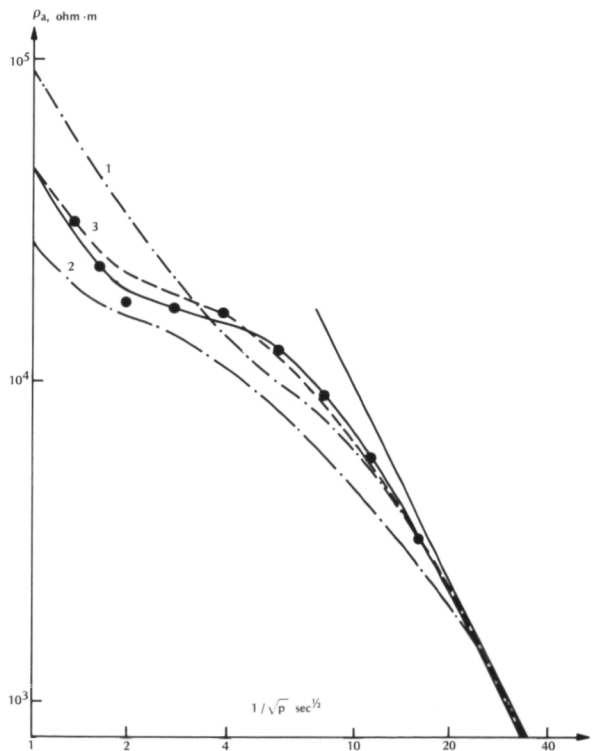

Figure 2.—*Comparison of experimental and theoretical apparent resistance curves.*

that was first found by the results of Apollo 12 (ref. 1).

However, the results of electromagnetic sounding most reliably distinguish an outer high-resistance shell about 200 km thick.

The results obtained permitted Fadeyev to make a preliminary petrological interpretation of the layers of the Moon (ref. 4). Their origin is probably a consequence of differentiation of the initial periodotite material. Upon melting, 20 to 40 percent of the material melts and is removed to form a high-resistance basaltic shell, underlain by a layer of spinel periodotites enriched in divalent iron oxides and having a reduced resistance, as shown by experiments. As is known, spinels are stable in the pressure range from 10 to 20 kbars, which corresponds to depths of 200 to 400 km; i.e., it is in agreement with the zone of reduced resistance. If one relies on the laboratory measurements of the electrical conductivity of terrestrial periodotites, the resistivity of 10^4 ohm·m found at depths of 400 to 500 km corresponds to a temperature of 600° to 700°C. This gives an average value of the temperature gradient of about 1.5 deg/km.

Acknowledgment

References

1. SONETT, C. P. et al., *Science*, Vol. 172, 1971, pp. 256–258.
2. BERDICHEVSKIY, M. N., L. L. VAN'YAN, AND E. B. FAYNBERG, *Geomagnetism i Aeranomiva*, Vol. 2, 1967.
3. VAN'YAN, L. L., AND I. V. YEGOROV, *Kosmich. Issled.*, Vol. 6, 1973.
4. VAN'YAN, L. L. et al., *Ann. Geophys.*, Vol. 29, 1973, pp. 367–374.