THE LUNAR LITHOSPHERE FROM ELECTROMAGNETIC-SOUNDING DATA

L. L. VANYAN and I. V. EGOROV
Soviet Geophysical Committee, Moscow, U.S.S.R.

(Received 4 February, 1976)

Abstract. Four sets of published data are used: frequency dependence of the day-side horizontal magnetic amplification, the same for the dark-side vertical decrease, the day-side transient amplification and the dark-side transient decrease. Transient data are transformed into the frequency domain and the dark-side data are transformed into the corresponding day-side horizontal amplification. Finally, all experimental results are presented in the form of the day-side frequency response. The summarised apparent resistivity curve is obtained by this response. It corresponds to the model with resistivity about several hundreds of $\Omega \cdot m$ to the depths of 700–800 km. It suggests the absence of significant amounts of molten material to these depths.

The idea of investigating the Moon's electromagnetic response – i.e., the relationship of horizontal components of magnetic variations on the illuminated side and radial components on the dark side to corresponding components of the external field – was proposed by American investigators in the late sixties. However, to carry out such a proposal seemed pointless until the direct problem of electromagnetic induction in an asymmetric model of the Moon with its 'cavity', taking account of the finite speed of propagation of a non-homogeneous external field, had been solved. In more recent years many papers were published showing that favourable conditions and regions existed under which a study of the lunar response could allow the electrical conductivity of the Moon to be determined independently of the parameters of the plasma envelope of the Moon.

Information about the electrical conductivity is contained in the frequency and time characteristics of the daily enhancement and the nocturnal decay. However these functions do not have the advantage of directness which, as is well known from experimental studies on the Earth, but refer to an apparent resistivity. As was shown by Vanyan and Egorov (1973), the apparent resistivity may be determined from the equation

$$\rho_a = -\frac{i\omega\mu a^2}{4\tilde{h}_T^2} \tag{1}$$

where $\tilde{h}_T$ is the 'daytime' enhancement and a is the Moon's radius. The meaning of the quantity $|\rho_a|$ is that of an average of the true resistivity with distance below the lunar surface up to the depth of penetration of the field of the given period $T = 2\pi/\omega$. Hence, the variation of $|\rho_a|$ with T obviously reflects a variation of the true resistivity with depth, which is very useful for an interpretation of the experimental data.

The apparent resistivity associated with the night-time decay may similarly be introduced as

The Moon 17 (1977) 3–9. *All Rights Reserved.*

$$\rho_a = i\omega\mu a^2\tilde{h}_n^2/9 \tag{2}$$

For initial conditions of the transient process we may write

$$\tilde{h}_T(t) = \tfrac{1}{2}a\sqrt{\mu/\pi\rho t}).$$

With the aid of this formula the apparent resistivity can be expressed as

$$\rho_a(t) = \mu a^2/4\pi t\tilde{h}_T^2(t). \tag{3}$$

Similarly for the night time decay

$$\rho_a(t) = \frac{\mu a^2 h_n^2}{9\pi t} \tag{4}$$

Generally the four functions (1) to (4) have an asymptotic behaviour as $\omega \to 0$ or $t \to \infty$, since, both for enhancements or decays they all tend to unity as $\omega \to 0$ and $t \to \infty$.

Under these circumstances

$$|\rho_a(\omega)| \approx 5.98 \times 10^6 T^{-1}, \quad \rho_a(t) \approx 3.03 \times 10^5 t^{-1}, \quad \text{day},$$

$$|\rho_a(\omega)| \approx 2.67 \times 10^6 T^{-1}, \quad \rho_a(t) \approx 1.33 \times 10^5 t^{-1}, \quad \text{night}.$$

From this it follows that if we represent graphically the behaviour of the functions (1) to (4), in terms of log $\sqrt{T}$ and log $\sqrt{t}$ as abscissae, and log $|\rho_a|$ and log $\rho_a(t)$ as ordinates, then each of the four curves will possess an asymptote in the form of a straight line inclined at the angle $-63^\circ\!.5$.

As is known from experimental studies of the Earth, the existence of asymptotes, limits the depth of electromagnetic sounding independently of the distribution of electrical conductivity, since close to an asymptote the apparent resistance ceases to depend on the conductivity distribution in deeper layers. To illustrate this in Figure 1, two three layer curves are compared for which the resistance of the third layer at depths greater than 740 km is compared. In spite of the fact that the resistivities at these depths differ by an order of magnitude, the difference in apparent resistivity does not exceed 25%. This circumstance then places additional requirements on the accuracy of the experimental data which would be needed for a more exact determination of the electrical condutivity of layers more than seven to eight hundred kilometers deep. As have been shown from simultaneous observations of the magnetic field by lunar satellite and at the surface, the increase of the horizontal component of the magnetic field in the frequency regime at the surface of the Moon reaches a factor of 3 to 5 for oscillation periods of around 20 to 30 s, and drops to unity in periods of about an hour. This decline reflects the gradual penetration of the electromagnetic field deep into the Moon. If the interplanetary magnetic field shows a sudden variation, then an analogous process may be observed in which an almost total decay of the induced currents and a magnetic increase of about thirty unity occur over an interval of several minutes after the arrival at the Moon of sudden variations.

Bursts of activity propagating outward from the Sun often show one important feature:

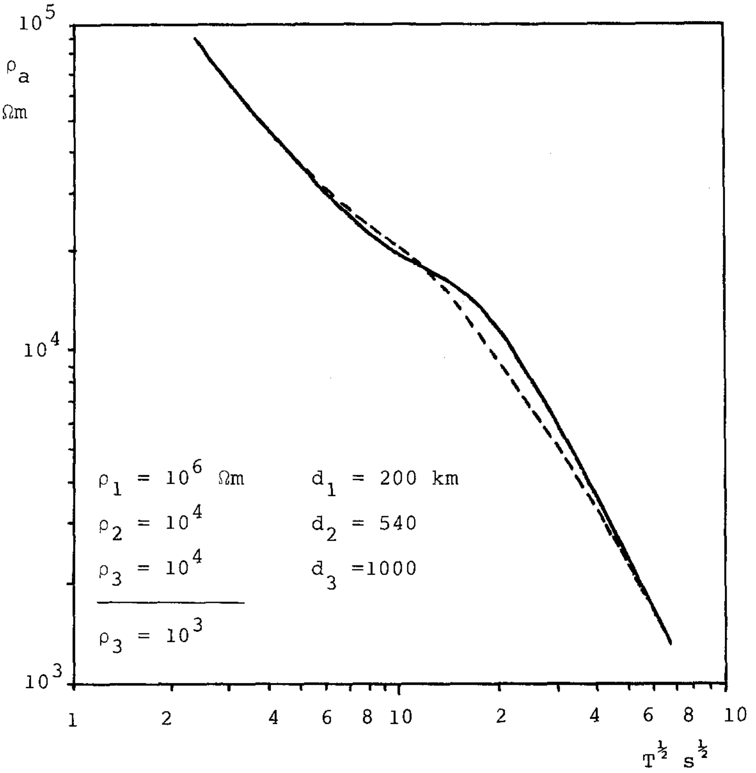

Fig. 1. Calculations of apparent resistivity for models with differing conductivity layers at depths down to 740 km.

their magnetic field is linearly polarized. This allows us to make use of the ratio of the horizontal component, for the illuminated surface of the Moon, to its steady-state value. The vertical component characterizes the variation of the external field. Hence, by hypothesis, the satellite measurements are no longer necessary.

The proposed method was followed in the analysis of a number of magnetic pulses registered by the magnetometer aboard the Lunokhod 2. The typical example of Figure 2 shows the meridional and vertical components of a magnetic field pulse registered at $0^h31^m35^s$ on March 23, 1973. The pulse data indicate that the vertical component differed a little from a sudden increase approaching a steady-state value after, typically, about 16 s: while the horizontal component first increased sharply, and declines thereafter eventually to stabilize at a constant level, in approximately 3 min.

The pulse of March 23 was registered when the solar wind velocity, exceeded, according to the Soviet Research Earth Satellite Prognoz 3 and the American Interplanetary Automatic Station Pioneer 9, some 730 km s^{-1}. This means that, for Fourier harmonics with periods in excess of 20 s, the effects of finite travel time of the disturbance in the solar wind past the Moon may be neglected in the process of electromagnetic induction.

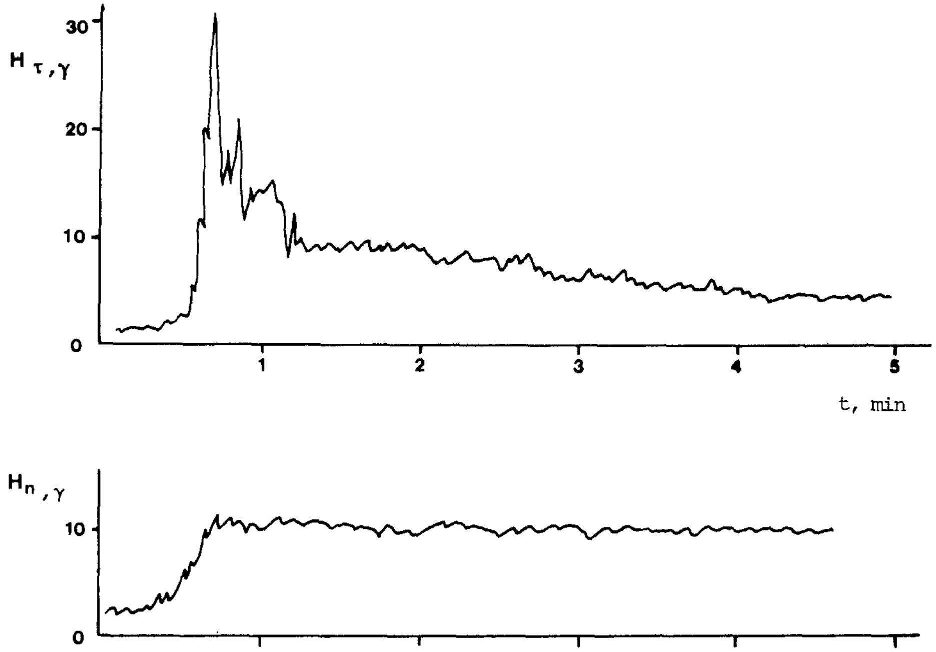

Fig. 2. Magnetic field pulse of March 23rd 1973 (Crater Lemonye).

In Figure 3 three crosses indicated the strengthening of the horizontal magnetic field, determined according to the pulse data registered on Lunokhod 2 and transformed to the frequency domain.

Let us consider more complete statistical data obtained at the time of the synchronized work of the magnetometers of Apollo 12 and Explorer 35. This data was published in the form of four independent characteristics. A group of investigators led by P. Dyal (cf. Dyal *et al.*, 1974) obtained the daytime enhancements and night time diminutions in the time domain. Sonett *et al.* (1972) published data of similar characteristics of the response of the Moon to variations of the interplanetary magnetic field in the frequency domain.

It would be very desirable to combine these four characteristics into one. Such a combination has been carried out in the present paper in two steps. As the first step, the frequency characteristics of the transient regime were obtained by means of a numerical Fourier transform. The second step was to relate night-time diminutions to daytime enhancements by the equation $3/\tilde{h}_n - 1 = 2\tilde{h}_\tau$ (Vanyan and Egorov, 1973). In this way a family of frequency characteristics for the daytime enhancements was found. A scatter between the different curves of the family served as a measure of the accuracy of the conductivity model of the Moon, since the velocity of propagation of interplanetary disturbances and the size of the plasma shadow affect the magnetic variations on the day and night time hemispheres quite differently in the frequency and time domains.

From the results of the Apollo 12 magnetometer we obtained the following curves which are shown in Figure 3:

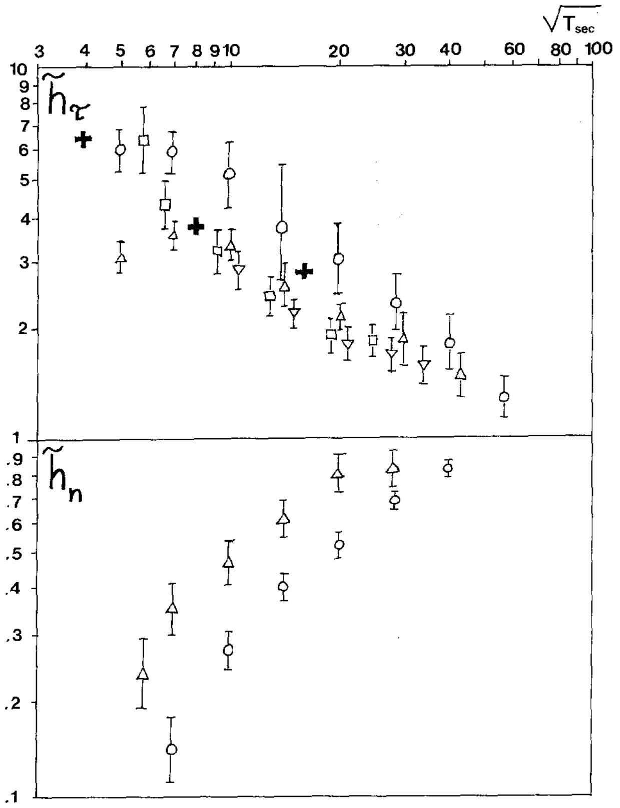

Fig. 3a. Summarized data on the frequency response of the Moon. △ – measurements of daytime enhancements and night time diminutions (Sonett *et al.*, 1972). ○ – Fourier transforms from transients of the daytime enhancement and night time diminution according to the data of Dyal *et al.* (1974). □ – daytime enhancements related to night time diminutions. ▽ – Apollo 15 data + Lunokhod 2 data.

(1) The daytime enhancement of the horizontal component in the frequency domain.

(2) The night time decline of the vertical component in the frequency domain.

(3) The daytime enhancement recalculated using the data of the second curve.

(4) The daytime enhancement in the frequency domain, derived from Fourier transforms of the enhancement function transients.

(5) The night time diminution in the frequency domain, obtained from Fourier transforms of the decay transients.

(6) The region of values of apparent resistivity which includes all apparent resistivity curves determined from the frequency characteristics of the lunar response.

As may be seen from Figure 3 the apparent resistivity attains 10^4 Ωm for $T \approx 25$ s and decrease to around 10^3 Ωm for $T \approx 10^4$ s.

The curves which are situated in the diagram inside the region of experimental values of apparent resistivity have been derived theoretically from the following models for the actual electrical conductivity:

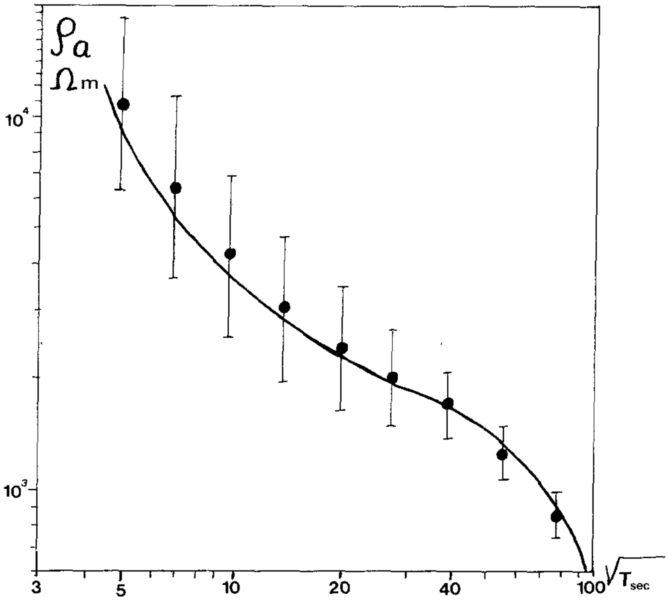

Fig. 3b. Summarizing curve of apparent resistance.

$\rho_1 = 10^6\,\Omega\text{m}$, $d_1 = 175\text{ km}$,

$\rho_2 = 5 \times 10^2$, $d_2 = 150$,

$\rho_3 = 2 \times 10^5$, $d_3 = 200$,

$\rho_4 = 5 \times 10^3$, $d_4 = 240$.

$\rho_5 = 5 \times 10^2\text{–}5 \times 10$;

Hence, the models of the Moon characteristic of the uppermost 700–800 km show actual resistivities in excess of $5 \times 10^2\,\Omega\text{m}$ which indicates a lithosphere without partial melting. Actually, as was shown by Honkura (1974), a small percentage of liquid phases rapidly lowers the resistivity. The appearance of 5 to 10% melts in rocks of specific resistance $10^3\,\Omega\text{m}$ lowers the resistivity to 15–40 Ωm.

One way in which the global character of the electrical conductivity distribution obtained by us can be confirmed is by a comparison of the response curves for different regions of the Moon. We already mentioned the agreement of curves over the steady field for Apollo 12 (Oceanus Procellarum) and Lunokhod 2 (Mare Tranquillitatis), separated by more than 1500 km. It is interesting to compare the results of Apollo 12 and Apollo 15 (separation about 800 km). According to the data of Sonett *et al.* (1974) the daytime enhancements found in the vicinity of the Apollo 15 landing area practically coincided with the results for the place where the Apollo 12 magnetometer was set for $\sqrt{T} > 14\,\text{s}^{1/2}$ (see Figure 3). This is an evidence for the global character of a massive lunar lithosphere.

Hence, the magnetic variation soundings permit us to restrict ourselves' only to those models in which the melting occurs at depths greater than 700 to 800 km. Magnetic variation soundings thus require a massive lithosphere occuping 45% of the lunar radius as compared to the 1.5% for the Earth. This conclusion about the depth of the rigid envelope of the Moon agrees well with the location of the centres of lunar tremors at depths of 500 to 800 km as with the extinction at these depths of transverse seismic waves.

Moreover, estimates of the size of the lithosphere from the results of electromagnetic sounding allow us to divide the lithosphere further into a high resistance outer envelope of thickness about 170 km, and a relatively conductive layer in the depth interval 170 to 320 km.

References

Dyal, P., Parkin, C. W., and Daily, W. D.: 1974, Soviet–American Conference on Cosmochemistry of the Moon and Planets.

Honkura, Y.: 1975, *Phys. Earth Planet. Inter.* **10**, 128.

Sonett, C. P. *et al.*: 1972, *Geochim. Cosmochim. Acta. Suppl. 3,* **3**, 2309.

Vanyan, L. L. and Egorov, N. V.: 1973, *Cosmic Studies*, No. 6.