Reports

Whole Body Response of the Moon to Electromagnetic Induction by the Solar Wind

Abstract. *A comparison has been made of the interplanetary magnetic field as measured both by Apollo 12 on the lunar surface and by Explorer 35 in orbit around the moon. Two examples are given, one of a step change in the field vector and another of a sinusoidally varying field. A large response measured on the surface is attributed to confinement of the induced field lines between the streaming solar plasma and the high-conductivity interior. A steep bulk electrical conductivity gradient in the lunar crust is implied, with a confining layer roughly 100 kilometers deep.*

Preliminary data from the Apollo 12 lunar surface magnetometer (LSM) and the Explorer 35 lunar orbiter define broad limits for the step and sinusoidal inductive response of the moon to magnetic fields convected in the solar wind. Explorer 35 data define the driving field or forcing function that excites the lunar response, whereas the LSM data give the summed driving and response signals. The data suggest a steep gradient in the bulk electrical conductivity in the subsurface layers of the moon. This latter conclusion depends upon the magnitude of the response which, on the sunward side of the moon exposed to the solar wind plasma, exceeds that of the equivalent vacuum induction by one-half to one order of magnitude (in the two cases discussed here). The electromagnetic boundary conditions require that a confining current layer in the solar wind also be present, close to the lunar surface. A permanent magnetic field of 38 gamma (1 gamma = 10^{-5} gauss) on the lunar surface has been measured by the LSM in Oceanus Procellarum. From combined measurements made with the LSM and Explorer 35 it is known that the source cannot be of global scale and that the strength p of the equivalent dipole, if the dipole lies near the surface, is in the range $3.5 \times 10^9 \leq p \leq 10^{18}$ gauss cm³ (*1*).

Figure 1 shows an example of transient induction. The dashed lines represent the driving field measured by Explorer 35, and the solid lines represent the response on the lunar surface detected by the LSM. The coordinate system used here is based on the moon's geometry. It is defined by a mutually orthogonal set of unit vectors $\hat{x},\hat{y},\hat{z}$ (vertical, eastward, and northward, respectively) at the location of the LSM. Local permanent magnetization (which suggests the possibility of a minor additional component of induction due to local permeability) is not important in an initial analysis.

On the basis of the theory of magnetohydrodynamic discontinuities, the perturbation detected by Explorer 35, shown in Fig. 1, is either a tangential discontinuity or an Alfvén wave (*2*). Either interpretation is consistent with the main points discussed here. At both magnetometer locations the magnetic field component B_x is approximately the same, an indication that little modification of this component can be assigned to effects originating in the

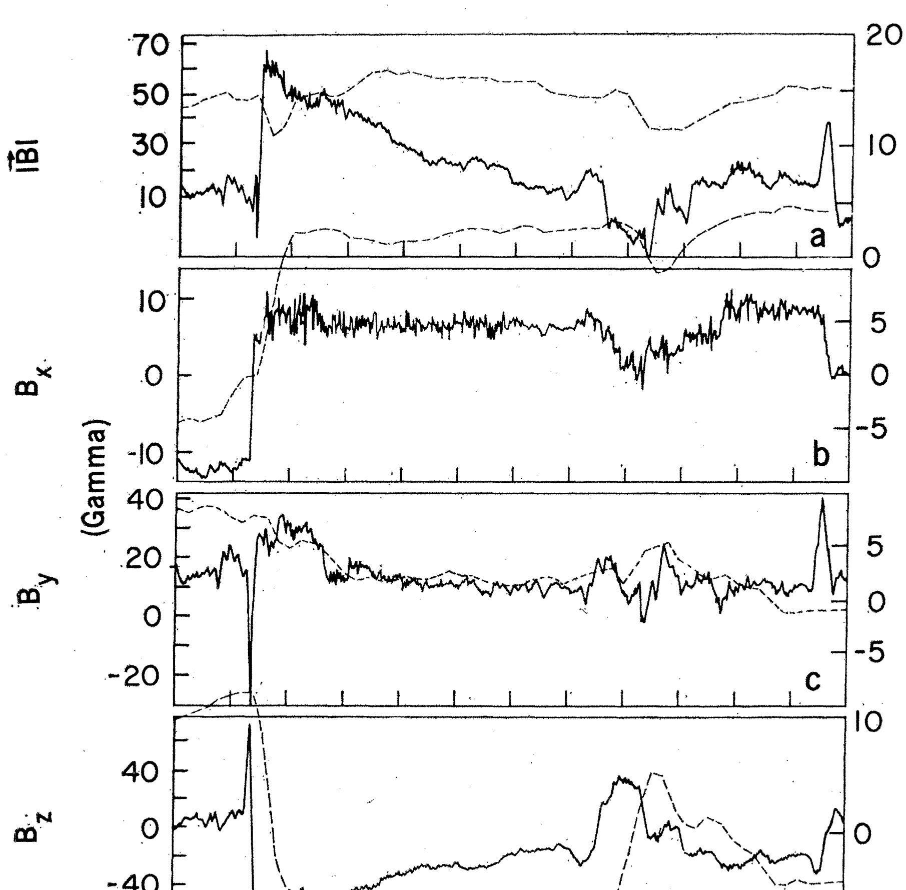

Fig. 1. Free-stream magnetosheath magnetic field (dashed lines) detected by Explorer 35 together with the lunar response at the LSM (solid line), showing the excitation of the moon by a tangential discontinuity convected by the solar wind. The field detected by Explorer 35 is shown on the right-hand ordinate and that detected by the LSM is shown on the left. The magnitude of the magnetic field is shown in (a) and the components are given for both cases in a coordinate system defined by the moon and described in the text (b–d). The sharp transients in the LSM y and z components are artifacts introduced by the digital filter and should be ignored.

moon. The magnetic field magnitude $|\bar{B}|$ shows only a temporary dip detected by Explorer 35, but there is a large step change in $|\bar{B}|$ measured at the LSM; examination of the components of the field discloses that the component most magnified is B_z. This component has an initial variation of about 14 gamma in the free-stream solar wind, whereas the change at the LSM is about 70 gamma. In addition to the very large amplification, a noteworthy property of the surface field is the decay to approximately the initial value in a time of 2 to 3 minutes.

If we assume that the response is representative of the whole moon, as suggested by other data (*3, 4*), then a crude "mean" conductivity can be estimated by means of a first-order decay, on the assumption that μ is equal to μ_0 (where μ is the material permeability and μ_0 is the permeability of free space), and that the response field is due primarily to a conducting core of radius 0.9 R_m (where R_m is the lunar radius), consistent with the result for the thickness of the confining layer. For an arbitrary sphere of uniform conductivity the eddy current decay may be characterized by a series of time constants with their amplitudes, weighted by n^{-2}, having values

$$\tau_n = \mu_0 \sigma L^2 / \pi^2 n^2 \quad (1)$$

where σ is the bulk electrical conductivity, L is the radius of the sphere, and $n = 1,2, \ldots$. Thus the bulk electrical conductivity is in the range $4 \times 10^{-4} \leq \sigma \leq 6 \times 10^{-4}$ mho/m.

The very large amplification suggested by the response indicates strong confinement of the eddy current magnetic fields to a thin crustal layer endowed with a conductivity substantially less than that of the deeper layers. Since values for the momentum flux of the solar wind in the free stream and on the lunar surface are not presently available, it is not possible to assess whether the magnetic pressure of the induced field exceeds that of the solar wind. The very large magnetic pressure associated with the step change does raise the possibility that complete confinement of the magnetic field does not take place. Consequently, it seems reasonable to conclude that either the excess field lines are blown toward the rear and collected temporarily in the diamagnetic cavity, or, if momentum transfer is efficient, that an incipient shock wave will form on the sunward side of the moon. In the latter case a transitory pseudomagnetospheric bubble of field partially devoid of plasma might be formed on the sunward hemisphere.

Our results for the decay time and the conductivity differ substantially from those of Ness who observed a tangential discontinuity from Explorer 33 and Explorer 35 when the latter was behind the moon (*5*). A decreased transient slope for a tangential discontinuity traversing the moon, suggested by Ness, for the particular geometry investigated, is associated with a transverse magnetic response (TM mode) whose *maximum* value is attained in the steady state or at zero frequency (*6, 7*). This mode, responsible for a bow shock wave, has never been observed on the moon (*3*). The observations reported here are therefore attributed to the more familiar transverse electric (TE) mode and the attendant induction dipole which describe eddy current excitation. Calculations to be reported elsewhere (*8*) suggest that the eddy current excitation is unobservable at the periselene of Explorer 35. Since the zero-frequency (steady-state) TM excitation of the moon is unobserved, the discontinuity observed by Ness appears to exhibit the normal differences of the interplanetary magnetic field observed at the two satellites (separated by about 55 earth radii).

We now turn to the harmonic response of the moon. We have selected a four-cycle wave of period 50 seconds observed from both Explorer 35 and the LSM (Fig. 2). The coordinate system is identical to that used in Fig. 1 (the permanent component of the field at the LSM has *not* been subtracted). In the case of this wave, the amplification at the lunar surface over the value measured at Explorer 35 is a factor of about 4 averaged over the available four cycles for the B_z component. This result confirms the effect of a confining current layer or, alternatively, the pressure of the solar wind. It is possible to make a very approximate calculation of

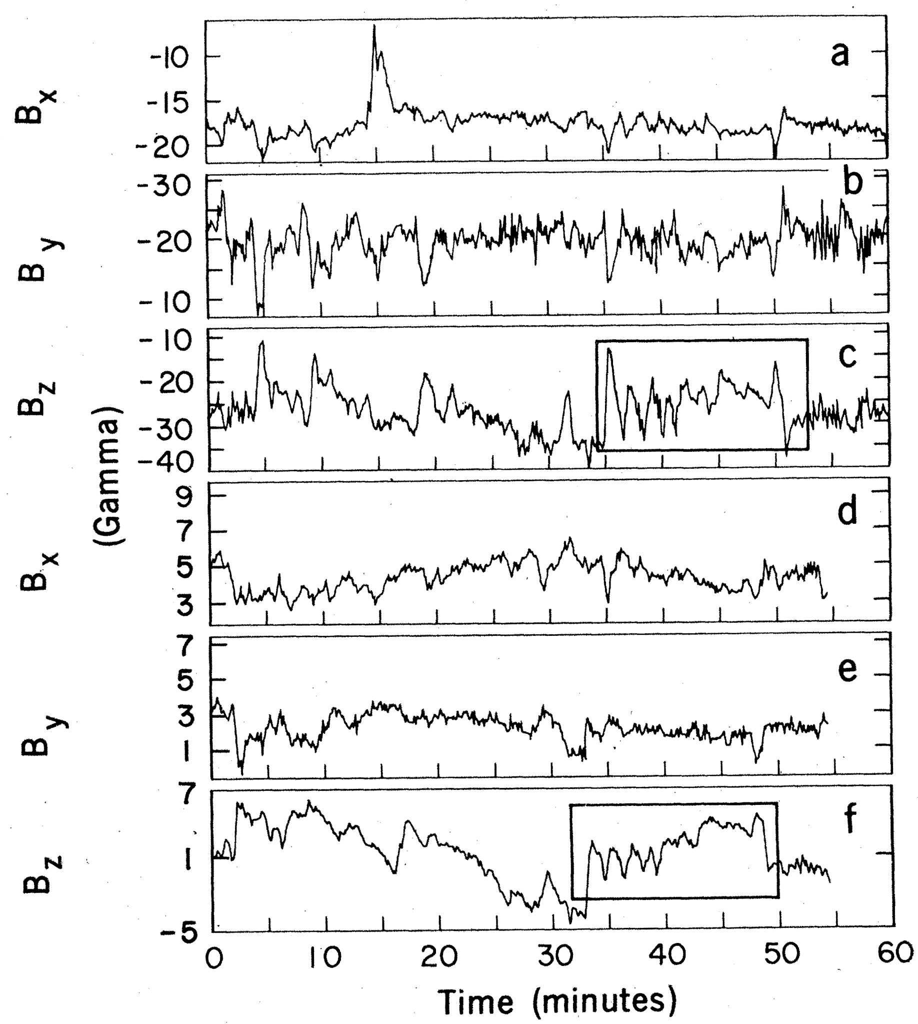

Fig. 2. Swaths of the LSM (a–c) and Explorer 35 (d–f) data showing a series of four cycles of a wave of period 50 seconds. The coordinate system is identical to that used in Fig. 1. The amplification of the LSM z component in Fig. 2 is discussed in the text.

the thickness of the low-conductivity outer layer of the moon. To do this the value for the "global" conductivity determined in Eq. 1 is used. In that equation it was assumed that the outer layer had zero conductivity, that the core possessed uniform conductivity, and that the wavelength of the exciting radiation from the solar wind was long as compared to the size of the moon. The dominant amplification of the TE mode can then be written as

$$A \cong \Delta^3 B_1 / (1 - \Delta^3 B_1) \qquad (2)$$

where $\Delta = R_c/R_m$, R_c is the core radius, and B_1 is an induction number for which values are tabulated (*6*). Examination of Eq. 2 suggests a confining layer approximately 100 km deep. Since the skin depth for the conductivity cited is of the order of 100 km, the value for the thickness of the crustal layer is only a rough approximation.

The principal conclusions to be derived from this preliminary report are that the moon exhibits an extraordinary level of induction from signals carried in the solar wind; the large amplification over that expected in a vacuum (when the induction is observed on the solar hemisphere of the moon) is indicative of a compression of a significant fraction of the induced field lines into a crustal layer of the moon where the bulk electrical conductivity is substantially less than that of deeper layers. Thus a model of the moon is suggested with a low-conductivity crustal layer overlying a core of higher conductivity. During the lunar night the response also shows about the same decay time but the amplification tends to unity, the response being more in keeping with the absence of plasma.

A conductivity gradient in the outer part of the moon is most likely associated with a thermal gradient since rocky matter, much like semiconducting material, exhibits an exponential dependence of conductivity on reciprocal temperature (*9*). Plausible lunar thermal models generally have thermal gradients in the range $1° \lesssim T \lesssim 5°$ per kilometer (*10*). Information presently available on lunar geochemistry is insufficient to permit us to judge the crustal thermal gradient. However, information on terrestrial olivines suggests that they may be effectively ruled out as a major constituent of the lunar crust unless the electrical conductivity of lunar olivines differs greatly from that of terrestrial olivines.

A complete Fourier analysis of the Explorer 35 and LSM magnetic field data (*11*) will include detailed tests for contributions from both the TE and the TM modes. These results will provide a complete electromagnetic transfer function for the moon. A formal inversion of these data into a conductivity profile is presently in preparation (*12*). In combination with appropriate geochemical information, the Apollo magnetometer experiment provides the unique potential for sounding the geophysical properties of the moon throughout most of its volume. The ability of electromagnetic radiation induced by the solar wind to penetrate to the center of the moon seems assured for the lowest frequencies under examination and appears to be unique.

C. P. SONETT, P. DYAL
C. W. PARKIN, D. S. COLBURN
J .D. MIHALOV, B. F. SMITH
National Aeronautics and Space Administration Ames Research Center, Moffett Field, California 94035

References

1. P. Dyal, C. W. Parkin, C. P. Sonett, *Science* **169**, 762 (1970).
2. D. S. Colburn and C. P. Sonett, *Space Sci. Rev.* **5**, 439 (1966).
3. D. S. Colburn, R. G. Currie, J. D. Mihalov, C. P. Sonett, *Science* **158**, 1040 (1967).
4. N. F. Ness, K. W. Behannon, C. S. Scearce, S. C. Cantarano, *J. Geophys. Res.* **72**, 5769 (1967).
5. N. F. Ness, *Nat. Aeronaut. Space Admin. Goddard Space Flight Cent. Rep. X692-70-141* (1969) [*Proceedings of the Solar Terrestrial Physics Symposium, Leningrad* (Reidel, Dordrecht, in press)].
6. G. Schubert and K. Schwartz, *Moon* **1**, 106 (1969).
7. J. L. Blank and W. R. Sill, *J. Geophys. Res.* **74**, 736 (1969).
8. C. P. Sonett, J. D. Mihalov, N. F. Ness, in preparation.
9. S. K. Runcorn, in *Handbuch der Physik*, J. Bartels, Ed. (Springer-Verlag, Berlin, 1956), vol. 47, p. 498; D. C. Tozer and J. Wilson, *Proc. Roy. Soc. Ser. A Math. Phys. Sci.* **296**, 320 (1967); T. Rikitake, *Electromagnetism and the Earth's Interior* (Elsevier, Amsterdam, 1966).
10. Z. Kopal, *The Moon* (Reidel, Dordrecht, 1969).
11. C. P. Sonett, B. F. Smith, D. S. Colburn, G. Schubert K. Schwartz, *Nature*, in press.
12. C. P. Sonett, G. Schubert, B. F. Smith, K. Schwartz, D. S. Colburn, *Geochim. Cosmochim. Acta*, Suppl., in press.

12 November 1970; revised 14 January 1971

Surface-Related Mercury in Lunar Samples

Abstract. *Lunar samples contain mercury, which may be volatilized at lunar daytime temperatures. Such mercury may constitute part of the tenuous lunar atmosphere. If mercury can escape from the atmosphere by a nonthermal mechanism, an interior reservoir or exterior sources (such as meteorite infall or solar wind, or both) are required to replenish it. Core samples exhibit an increase in surface-related mercury with depth, which suggests that a cold trap exists below the surface. The orientation of rocks on the lunar surface may be inferred by differences in the amounts of surface-related mercury found on exterior and interior samples.*

Mercury is volatilized from lunar material at temperatures as low as that reached during lunar daytime, 130°C (*1*). The presence of this Hg and its distribution between the exterior and interior of rocks and in core samples from different depths could prove useful in understanding the behavior of volatiles on and in the moon. We report here the results of studies on the surface-related Hg in lunar samples. Surface-related concentrations of a number of other elements have been reported (*2*).

Two reservations must be kept in mind with regard to Hg on surfaces. One has to do with the possibility of contamination; the other with the effect of gases (N_2 and water vapor) on the properties of surfaces. The possibility of contamination can be assessed. The effect of gases requires evaluation of the consequences of exposure of the ultraclean vacuum-pumped and, in the case of exposed surfaces, vacuum-sputtered surfaces to gases that can be adsorbed. These compete for adsorption sites or may chemically alter the surface. The result of such exposure could reduce the amount and adhesiveness of the Hg on surfaces. Therefore, the concentrations measured may be lower limits, if losses have occurred, and the fraction released at lower temperatures may be upper limits because of increased lability.

There are several lines of evidence against terrestrial Hg contamination. Samples were obtained from the Lunar Receiving Laboratory (LRL) as powders (soil and crushed rock) and as rock fragments. All sample handling, including the crushing of rock fragments, was done in an N_2 box in our laboratory. The amount of Hg volatilized at low temperatures showed no systematic variation. The core samples opened at LRL should have had equal opportunity to become contaminated by volatiles; however, the sample from the top of core 10004 released 0.24 parts per billion (ppb) of Hg at tem-