INDUCED AND PERMANENT MAGNETISM ON THE MOON: STRUCTURAL AND EVOLUTIONARY IMPLICATIONS

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Abstract. It is shown that the Moon possesses an extraordinary response to induction from the solar wind due to a combination of a high interior electrical conductivity together with a relatively resistive crustal layer into which the solar wind dynamic pressure forces back the induced field. The dark side response, devoid of solar wind pressure, is approximately that expected for the vacuum case. These data permit an assessment of the interior conductivity and an estimate of the thermal gradient in the crustal region. The discovery of a large permanent magnetic field at the Apollo 12 site corresponds approximately to the paleomagnetic residues discovered in both Apollo 11 and 12 rock samples The implications regarding an early lunar magnetic field are discussed and it is shown that among the various conjectures regarding the early field the most prominent are either an interior dynamo or an early approach to the Earth though no extant model is free of difficulties.

1. Introduction

Until recently it was generally held that the Moon was an electromagnetically inert object, though Gold proposed some years ago that a bow shock wave should be a persistent feature when the Moon was in the solar wind [1]. None of the early space probe attempts at assessing a permanent field or interaction effects perceived a signal above threshold [2]. Also one prominent view, that the Moon is cold, decreased the likelihood that the Moon had ever possessed a magnetic field. An additional constraint upon refined analysis of data suggesting a lunar effect upon the magnetosphere was beclouded by the nearly commensurate lunar orbital period and the rotation period of the Sun.

Recently, it has become possible to investigate the neighborhood of the Moon extensively using the Explorer 35 lunar satellite which carries two magnetometers and a variety of other experiments [3, 4, 5, 6]. The several findings of particular importance to electromagnetic response to induction by the solar wind and the question of permanent magnetism are discussed in this paper; other findings which are peripheral to these problems are not considered. Their general importance is not thereby diminished but the relevance is limited. The most recent experiment was the placement of the Lunar Surface Magnetometer (LSM) at the Apollo 12 site as part of the complement

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of experiments left upon the surface [7]. The induction and steady field problems are conceptually attacked by use of the combination of Explorer 35 and the LSM and the discussion to follow will consider data from both.

The experiment to detect and analyze electromagnetic induction rests upon analysis of the incident magnetic signals in the solar wind using Explorer and the detection of the combined response and incident signal on the lunar surface (constituting a scattering experiment in the formalism of electromagnetic theory) [8]. Some modification to the vacuum theory is required because of the remarkable effect that the dynamic pressure of the solar wind plasma has upon the induced field; formally this constitutes a change in the usual boundary conditions. The fact that the Moon displays a strong induction signal and that this can be used to provide information regarding the deep profile of electrical conductivity and from this by an inversion, the thermal profile, is a new effect which can be exploited in depth. This paper is a summary progress report; the data from the Explorer and LSM jointly cover the period beginning in Nov. 1969 and thus analysis is still in an early stage. Therefore, the comments made should be viewed as preliminary and subject to modification insofar as quantitative conditions are discussed. It is likely that further work will disclose effects which are not apparent at the present time.

2. The Interplanetary Electromagnetic Field

The solar wind is known to be comprised primarily of an equal density of ions and electrons each having a value of about $5\ \mathrm{cm}^{-3}$ during quiet times. Additional increments of other (heavier) ions are known to exist but are unimportant in the present discussion. The temperature of the plasma is divided into that due to the ions, T_i and an electronic component, T_e. T_i is further divisible into parallel and perpendicular components referred to a coordinate system fixed by the direction of the magnetic field. This anisotropy is unimportant in the present case of a first order discussion of the lunar interaction, but could be included in a refined treatment. The values of T_i and T_e are variable, ranging for T_i from less than 5×10^4 K to more than 5×10^5 K in extreme cases. The value of T_e is likewise thought to be variable but its range is less certain, since the measurement of this quantity is considerably more difficult than for T_i.

The interplanetary magnetic field, **B**, is likewise variable having a mean quiet value of about 5γ ($1\ \gamma=10^{-5}$ G). It has the special property of being spiralled because of a combination of solar rotation, high electrical conductivity of the plasma, and the outward flow of the latter, which during quiet times has a value of order 400 km/sec. The spirality of the field increases with distance from the Sun in accordance with the argument of Parker where the field components are given by

$$B_r = B_{r_0}\left(\frac{r_0}{r}\right)^2; \quad B_t = \frac{\omega r}{v_s} B_r,$$

where B_r and B_t are respectively the radial and tangential components of the magnetic field, r_0 is the solar radius, r the distance from the center of the Sun to the point of

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observation in the vicinity of the Moon, ω the angular rotation rate of the Sun, and $\mathbf{v}_s$ the bulk convective speed of the solar wind assumed radially directed (Figure 1), though small deviations occur. In fact in the steady state a deviation from radiality is expected in the frame commoving with a spacecraft or planet due to the apparent aberration of the direction of flow, analogous to the aberration of starlight.

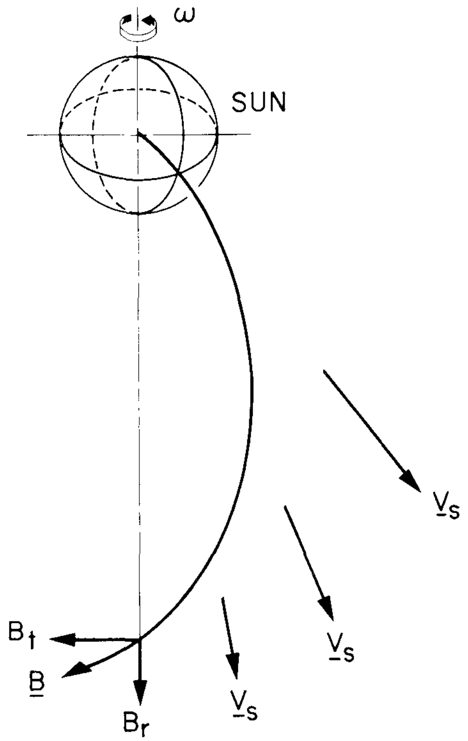

Fig. 1. Schematic view of the interplanetary field formed by field lines carried out from the Sun by the solar wind, $\mathbf{V}_s$, and the rotation of the Sun, ω. The field is resolved for the present discussion into components, B_r radially out from the Sun and B_t transverse to B_r. There is no mean component out of the ecliptic.

It is these quantities which form the framework of the discussion regarding the electromagnetic interaction between the Moon and the solar plasma. In spite of the expected anisotropy of the electrical conductivity in the solar wind due to the magnetic field, it is generally held that the overall conductivity is sufficiently large so that a steady electric field cannot be maintained. This statement is not exact since polarization charges reside in the solar wind, but the subject of these lies outside the province of this paper and is not sufficiently important in this first assessment. The assumption of perfect electrical conductivity and the attendant lack of steady electric fields means that in any other frame, such as one commoving with a planet, there is expected to exist an electric field by virtue of the Lorentz transformation between the two frames. This field, $\mathbf{E}_m = \mathbf{V}_s \times \mathbf{B}$, results in the complete polarization of an object in the event that direct electrical contact with the solar wind is forbidden. Details of the argument are given elsewhere and we merely quote the consequences here [9, 10]. If electrical paths are developed, then currents flow through the planet closing in the solar wind, and attendant magnetic fields are present which supply a back pressure upon the solar wind. In the event of a strong interaction, it is found that a bow shock wave will develop. This mode of interaction is commonly called toroidal from the form of the magnetic field. Electromagnetically it can be referred to as transverse magnetic (TM). The mode has the property that its maximum value is attained in the steady state, i.e., when $d/dt\,(\mathbf{V}_s \times \mathbf{B}) = 0$ and asymptotically approaches zero with increasing time rate of change of the quantity E_m [11, 12].

The foregoing statements are important to note, for the form of the interaction of the Moon with the solar wind must be understood electromagnetically in order to carry out a quantitative assessment. The TM mode is augmented by the TE or transverse electric mode, also called poloidal. The latter corresponds to the familiar case of eddy current excitation. In this instance closure of currents through the planetary surface is not required, and the information gleaned from the strength of the interaction provides data on the electrical conductivity of the core of the planet (Figure 2).

The TE mode has a different frequency behavior than that of the TM mode. For the TE mode the frequency dependence of the interaction attains an asymptotic value at some frequency determined by the constitutive parameters of the planet, becoming

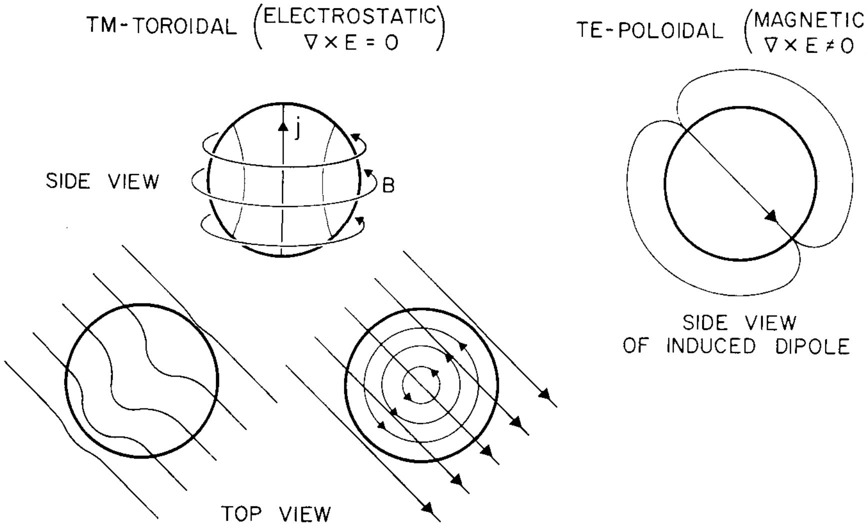

Fig. 2. Conceptualized view of the two primary modes of electromagnetic excitation of the Moon by the solar wind field. The TM or toroidal mode is shown on the left side of the figure. The lines of the induced field are shown at the top as closed circles about the Moon while the current streamlines flow through the Moon closing in the solar wind. On the left is shown the idealized configuration obtained by vector addition of the induced and forcing fields, while on the right are seen the two fields superimposed, but not added. The right hand side of the figure shows the TE mode, but only the magnetic field lines are given; the electric field forms in closed loops complementary to the TM mode.

zero as $\omega \to 0$. It should also be noted that the *TM mode corresponds to the case of field line dragging* and is identified with earlier versions of the lunar interaction where the diffusion of field lines through the Moon was invoked. However, the latter statement ignores the critical role of electrostatic fields which accompany this interaction and the importance of the crustal conductivity. Thus a highly conducting core shows no interaction if shielded from the solar wind by an atmosphere, a resistive crust, or a large permanent magnetic field about the planet. Because of the apparent magnetohydrodynamic nature of the interaction in the TM mode, it can be thought of as decreasing the apparent rise time of a discontinuity in the solar wind which passes through the Moon [9, 13]. This must not be mistaken for a Cowling time; the latter is associated with the TE mode where the response of the Moon is essentially instantaneous except for the inertia of current carriers, while the induced currents decay at a rate governed by the interior conductivity and show the apparent quasiexponential behavior associated with the decay process.

In discussing this problem attention is directed to certain characteristics of the plasma neighborhood of the Earth which are especially relevant to the experiment.

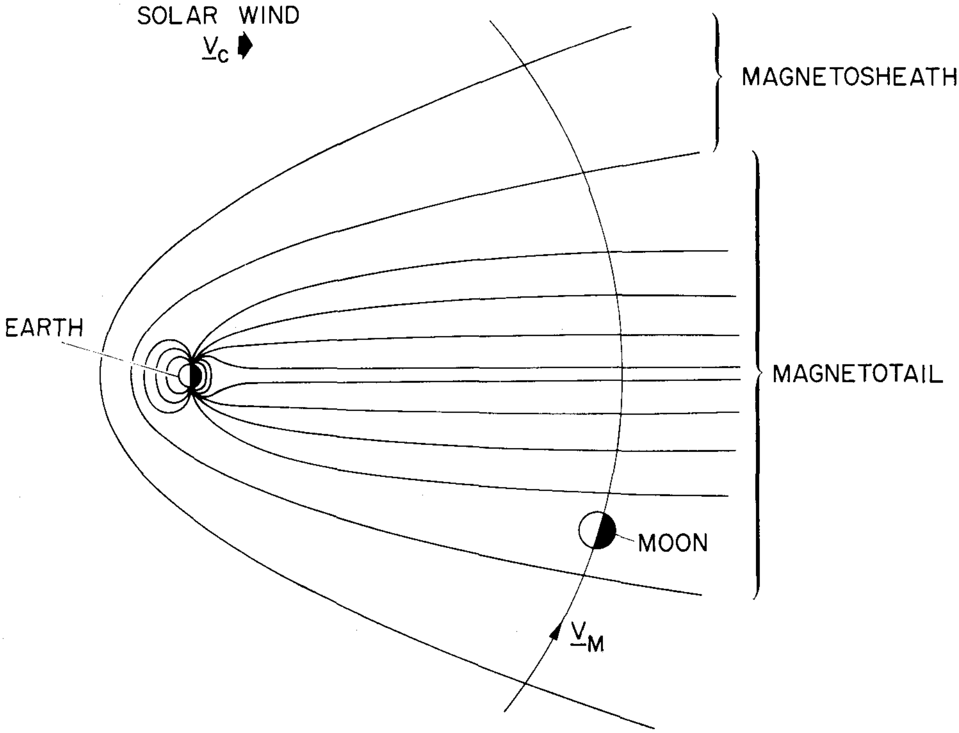

Fig. 3. Idealized view of the traversal of the Moon through the three primary magneto-hydrodynamic regions in the neighborhood of the Earth. The bow shock is formed by the outermost line of the magnetosheath, and the junction of the magnetosheath and magnetotail define the magnetopause. Each of these two regions together with the free stream solar wind are important in electromagnetic excitation of the Moon for different reasons which are discussed in the text.

The Moon orbits through the magnetic tail of the Earth for a period of about four days about full Moon. Any interaction with the plasma in the tail is strictly sub-characteristic to any of the wave modes of a collision-free plasma as the Alfvén speed in the tail is of order 500–1000 km/sec because of the low plasma density while the speed of the Moon is only about 1 km/sec. Any magnetohydrodynamic manifestation of an interaction would be undetectable with present instruments. Thus a vacuum model can be utilized. During quiet times in the tail the search for a steady magnetic field would be most favored.

The remainder of the lunation is spent in the free stream solar wind and in the shocked solar plasma of the magnetosheath. During these times a magnetohydrodynamic interaction might be present depending upon the intensity of the induction in the Moon. The different regimes are shown schematically in Figure 3.

3. Relevant Explorer 35 Results

In this section we discuss certain results from the Explorer 35 lunar orbiter which apply in detail to the analysis of the lunar response. First Explorer detected no measureable permanent global magnetic field in the neighborhood of the Moon [3, 4, 6, 14]. This places an upper bound on the moment of a permanent centered dipole of 10^{20} G cm^3. This result is to be compared with the earlier measurements of Lunik 2 and Luna 10. The former measurement made in 1961 used a magnetometer having a threshold of 30 γ. The last measurement prior to impact was made at an altitude of 55 km and showed no lunar field. In 1966 Luna 10 disclosed a 15 γ field in the lunar environs [2] but this was later identified as due to the magnetic tail of the Earth [6]. Thus to date there has been no detectable field noted from above the lunar surface. This permits the conclusion to be drawn that the steady state conditions imply the surface of the Moon to be in direct contact with the solar wind. This conclusion is confirmed by measurements using the Apollo 12 plasma probe [7] and the Al foil experiments of Apollo 11 and 12 [15]. In addition Explorer 35 detected no measurable steady state shock phenomena near the Moon [3, 5]. We restrict then, because of the peaking of the frequency response of the TM mode at $\omega = 0$, the discussion of the response of the Moon to the more apparent TE mode. *Field line dragging appears to be unimportant, except perhaps as a transitory state during the application of a large discontinuity from the solar wind.*

An additional result of the Explorer 35 experiments is that the rear or dark side of the Moon shielded from the direct solar wind displays a strong diamagnetic effect [3, 5]. That is the interplanetary magnetic field is enhanced by approximately 50% for the most extreme case. This finding is important in the calculation of power spectra since it varies with time and therefore can serve as a source of contamination. We shall discuss this point later. The variation of the diamagnetism is due to time variations in the product $nk(T_i + T_e)$ which can display excursions as large as a factor of 10 or more [16]. In considering this effect it should be noted that the cavity can be thought of as exterior to the solar wind in a topological sense. From this argument it is easy to see qualitively why such an effect should be present. Stated alternatively the *solar wind magnetic field* is depressed by an equivalent amount. Using this argument it follows that the interior of the Moon should formally display equivalent diamagnetism, i.e., the magnetic field should be continuous from the interior of the cavity on into the interior of the Moon when traced across the dark side of the lunar surface. The conclusion is that there may exist a diamagnetic discontinuity on the *sunward side* of the Moon whenever the cavity diamagnetism is displayed. This argument can be arrived at from other considerations connected with the particle intersections with the surface of the Moon [10]. Since the diamagnetism is variable, the time variation will contribute to the Fourier spectrum of variations on the sunward surface.

4. The Pulse Response of the Moon

Turning to the actual lunar response it is convenient to make a division into the pulse response and that due to the continuum background radiation field in the solar wind. In either case $\mathbf{E}_m$ in current analyses appears unimportant, and the response is attributed primarily to changes in $\mathbf{B}$. As it turns out the electromagnetic response of the Moon is anomalously large on the sunward hemisphere. An example of the response is shown in Figure 4, where both the incident discontinuity in the solar wind is shown with dotted lines and the lunar response with solid trace. The coordinate system employed here and elsewhere in this paper is as follows: The unit vector $\hat{x}$ is normal to the surface of the Moon and positive outwards, $\hat{z}$ is positive in the direction of local north, and $\hat{y}=\hat{z}\times\hat{x}$ is positive toward local east, forms the third member of the mutually orthogonal triad of vectors. Figure 4 identifies the discontinuity in the solar wind as tangential for there is little change in the magnitude of the field (it is possible that all the apparent change is assignable to the filter which follows the magnetometer system in the spacecraft.) On the other hand a very large change is witnessed in the magnitude of the field on the surface of the Moon. This can be traced to a large change in the z component of the field at Explorer. The change in the amplitude of the z component is approximately a factor of five showing that the induction is anomalous compared to that expected for the equivalent vacuum case.

The large induction signal is attributable to the momentum flux of the solar wind which forces the induced field lines back into the lunar surface. This view is reinforced by examination of the pulse response on the dark side shielded from the solar wind. This is shown in Figure 5 and indicates a response more in line with that expected from the vacuum case. In both cases the initial decay time for the induced pulse is of order three minutes. The decay time of a pulse in a homogeneous sphere is given by a series of time constants with amplitude weighted by n^{-2} [17]

$$\tau_n = \frac{4\mu\sigma R_{m^2}}{\pi n^2} \tag{1}$$

where σ is the bulk electrical conductivity, μ the magnetic permeability, R_m the scale

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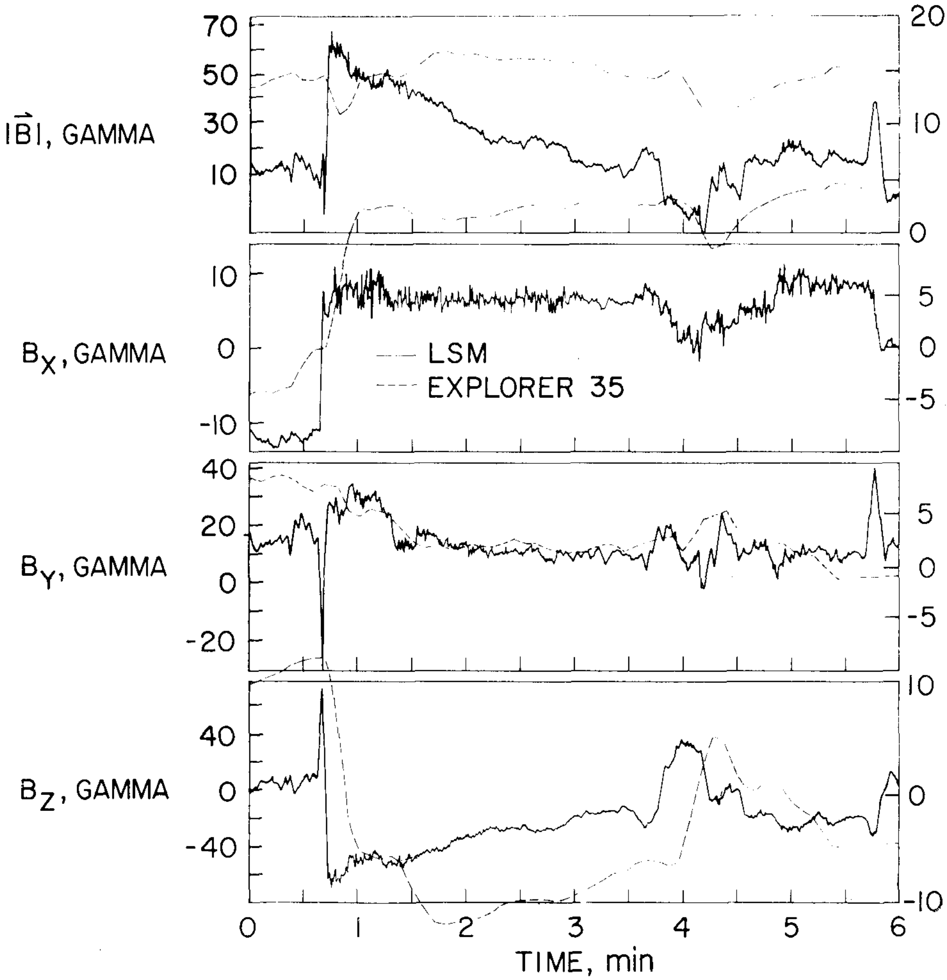

Fig. 4. Data from Explorer 35 (dashed lines) and Lunar Surface Magnetometer (LSM) showing the amplification of the free stream tangential discontinuity observed at Explorer when seen at LSM. The coordinate system is discussed in the text. The amplitude of the field is at the top while the three components for each magnetometer are shown in a common system in the following three diagrams. The left side ordinate corresponds to LSM fields and the right side to Explorer 35. The spike in the data at the onset of the pulse is a filter artifact and should be ignored.

size (here the radius of the Moon), and $n=1, 2, \ldots$ represents the order of response. When the sphere has $\mu > \mu_0$, μ replaces μ_0 and n' replaces n in (1), where $n \lesssim n' \lesssim 1.03n$ for all n and $\mu < 1.3\,\mu_0$. (The more complex case of a spherical shell has Cowling times given in terms of roots of a transcendental equation involving the Bessel functions of non-integral order, $J_{\pm 1/2}$ and $J_{\pm 3/2}$). As the lowest order dominates the response for the case of the homogeneous sphere we calculate that the effective conductivity of the Moon using a homogeneous model having a radius 0.9 to 0.95 R_m is about 10^{-4} $m$hos/m. This corresponds to a depth of about 100–200 km, which is the

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level where the bulk of the currents flow. Further it is clear from the strong amplification on the sunward side and the compression of the field lines that the Moon can qualitatively be described as having a conducting core surrounded by a much less conducting crustal layer of perhaps several hundred km thickness [17]. The effects are shown schematically in Figure 6.

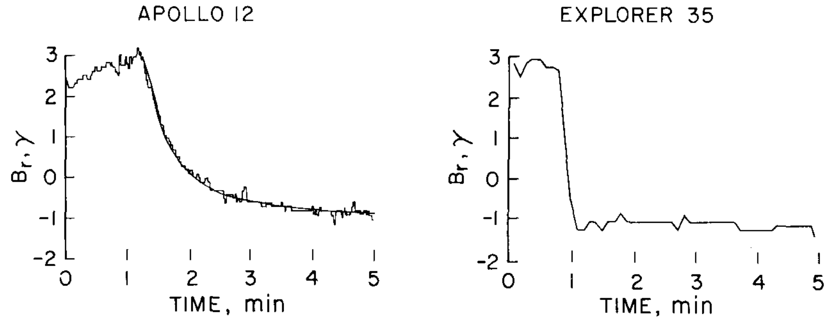

Fig. 5. Transient response of the rear (dark) side of the Moon to excitation by a solar wind tangential discontinuity. The driving field is shown on the right, while the LSM response is given on the left side of the figure. The decay at LSM is about three minutes, approximately the same as for the front side exposed to the solar wind (See Figure 4), but the amplitude of the response is reduced greatly.

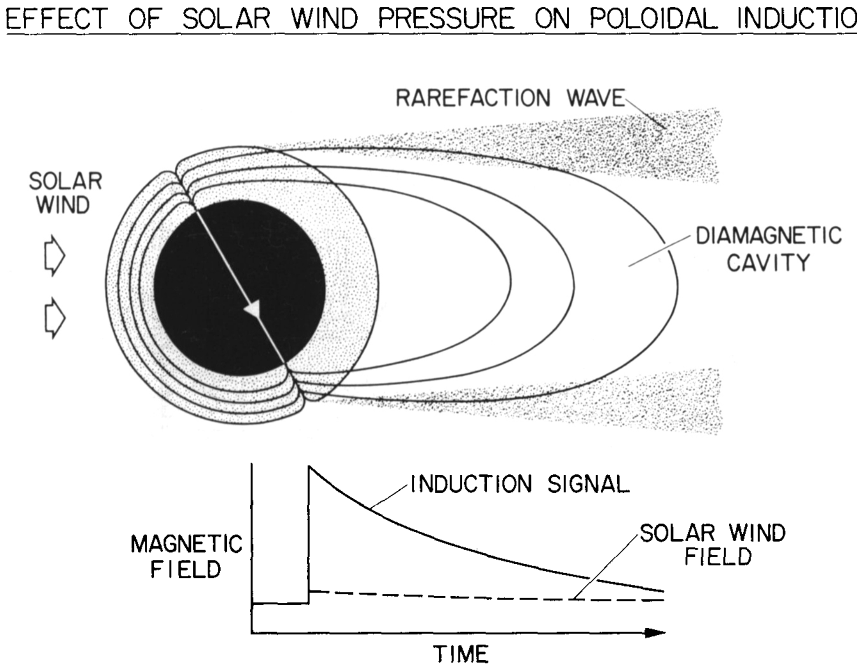

Fig. 6. Schematic view of the compression of field lines on the forward side of the Moon due to the pressure of the solar wind. Also sketched in are the rarefaction wave and diamagnetic cavity caused by stopping the solar wind flow by the target cross section of the Moon. An idealized induction signal for the TE mode is shown below.

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These conclusions regarding the pressure effect of the solar wind are tantamount to a surface current layer just ahead of the Moon residing in the solar wind. This comment is important from the theoretical standpoint since a model calculation permits the ram pressure of the solar wind to be regarded in terms of the boundary current layer. The ram pressure argument is augmented by noting the lunar dark side pulse response shown in Figure 5 lacking the strong amplification.

5. Harmonic Response

The complete analysis of the lunar response requires that the Fourier spectra at Explorer 35 and LSM be compared in detail. Computations are presently in progress and only a very preliminary account can be given here. Before turning to this, attention is directed to a particular case where four cycles of a wave of period 50 sec were observed at both Explorer and LSM. This wave is shown in Figure 7 using the same coordinates as in the previous case. The amplification has mean value 4.7 for the four cycles and is due primarily to induction from the $\hat{z}$ component of the interplanetary magnetic field. Schubert and Schwartz [11] have shown how, using a two layer model for the Moon, it is possible to extract both the conductivity corresponding to a par-

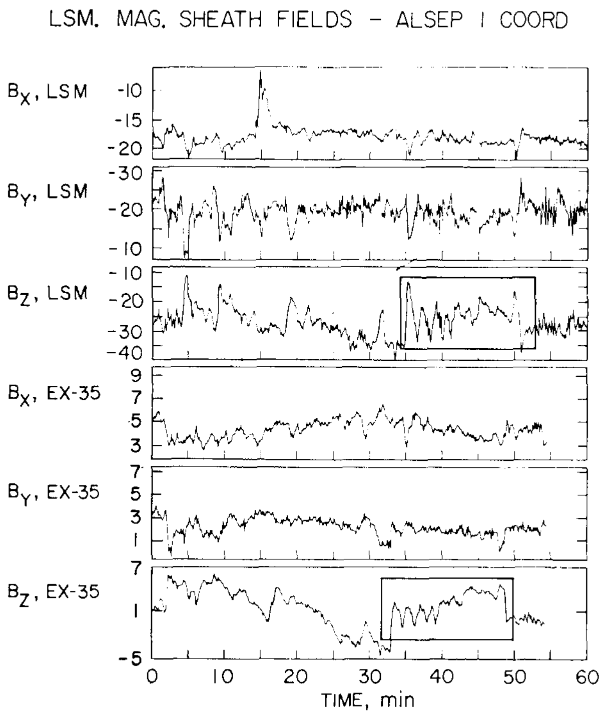

Fig. 7. Lunar response to a harmonic wave of period 50 sec indicated by both Explorer 35 and LSM as in Figure 4. The amplification of the signal at LSM is a factor of 4.7. The data is taken while the LSM is on the solar wind side of the Moon.

ticular frequency and to ascertain a measure of the depth of the pertinent level where the bulk of the currents flow. Their equation for the amplification is given by

$$A(\omega) \sim \frac{\Delta^3 B_1}{1 - \Delta^3 B_1} \tag{2}$$

where $A(\omega)$ is the amplification, B_1 an induction number which is tabulated elsewhere,* and $\Delta = R_c/R_m$ where R_c is the core radius and R_m the lunar radius as before. The conclusions from application of Equation (2) are similar to those from the pulse analysis and indicate the presence of a layer of conductivity about 10^{-4} $m$hos/m at a depth of 100–200 km [17] as witnessed in the pulse case. In the derivation of Equation (2) the boundary conditions include the presence of the postulated surface currents; in this way the pressure effects of the solar wind are accounted for without the necessity of developing a complete magnetohydrodynamic model. This statement is inexact when, as in the case of Figure 4, it is likely that the back pressure of the induced field upon the solar wind is large. Then the field can affect the flow of the plasma with the final result that excess field lines are swept to the dark side of the Moon and entrained in the diamagnetic cavity.

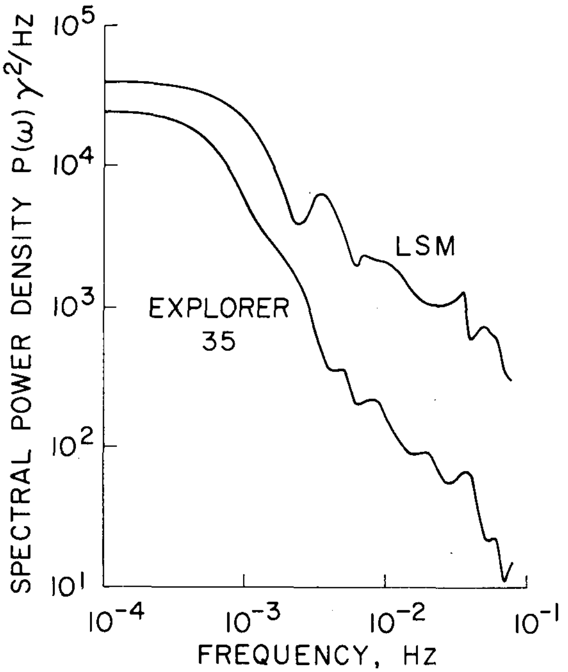

Fig. 8. A representative differential power spectrum of the field amplitude taken at both Explorer 35 and LSM. The spectrum is of the form approximately f^{-1} at LSM and f^{-2} at Explorer 35 over a substantial part of the frequency domain. This is consistent with the amplification of hydromagnetic signals at the surface of the Moon and their increase in intensity with frequency.

* B_1 is zero at $\omega = 0$ and rises to an asymptotic value of unity with increasing ω.

Fourier spectra (see Figure 8) calculated from the time series of the field show significant variability. It is possible that this is due to the time variations of the diamagnetism of the solar wind.* In spite of these variations it is possible to make a general assessment of the spectra so far obtained. These are displayed in the form of transfer functions which are defined as the lunar response divided by the interplanetary forcing function derived from Explorer. The transfer function is developed for all three components of the magnetic field and the primary information is contained in the frequency dependence. In general most of the amplified power resides in the two tangential components, $\hat{y}$ and $\hat{z}$ and the transfer function power increases with frequency which is the behavior expected for a steep conductivity gradient. The variations in the $\hat{x}$ transfer function are relevant to determining depths but the present spectra require refinement in order to carry this out with conviction.

6. Determination of the Thermal Gradient in the Outer Layer

The complete solution to the problem of determining the thermal profile in the Moon requires inversion of the electrical conductivity profile using the temperature dependence of the bulk electrical conductivity. Information on the electrical conductivity at increasingly greater depths becomes difficult to ascertain from the surface response since this response becomes more sensitive to noise background and to the reduction in signal level due to the increased distance of the field producing layers of current from the magnetometer. An alternative approach to determining the thermal profile at all depths is to determine the approximately linear thermal gradient in the outer layers and match this gradient to thermal models of the Moon where the near surface gradient is related to the core temperature. This procedure is somewhat more model dependent but can serve as an important guide to later work upon the problem. It also relies on the determination of the thermal dependence of the bulk electrical conductivity of the basement rock, and in a sense by-passes the direct finding of the electrical conductivity profile which is decoupled from the thermal dependence of the conductivity. Eventually of course, this dependence must be brought in if the thermal profile is to be deduced from that of conductivity.

We have carried out the alternative approach of finding the thermal gradient in the near surface region. The details of this method will be reported elsewhere. Here we summarize the major results. The surface tangential transfer function for the lowest order spherical harmonic of the lunar TE response is presented in Table I for various values of frequency and thermal gradient and for two electrical conductivity functions. A comparison of the values of the experimental transfer function at the appropriate frequencies with the amplifications given in Table I allows the following conclusions. For the preliminary conductivity function of an Apollo 11 crystalline basalt (10024–22) determined by Nagata *et al.* [18] the near surface temperature gradient is 2 K/km while for the conductivity function typical of a terrestrial olivine [19] this temperature gradient

* An example of other possibilities is the generation of plasma instabilities in the plasma sheath just ahead of the Moon.

TABLE I

Surface tangential transfer function of lowest order spherical harmonic for the TE mode

Preliminary lunar rock conductivity function [18]		
Frequency	Real part	Imaginary part
	2, 3, 4 K/km	2, 3, 4 K/km
0.02 Hz	3.71, 5.25, –	−0.53, −0.77, –
0.04 Hz	4.58, 6.34, 7.99	−0.81, −1.00, −1.19
Terrestrial olivine conductivity function [17]		
Frequency	Real part	Imaginary part
	4, 5, 6, 7 K/km	4, 5, 6, 7 K/km
0.02 Hz	3.77, 4.62, 5.33, –	−0.53, −0.71, −0.83, –
0.04 Hz	4.66, 5.60, 6.47, 7.31	−0.73, −0.85, −0.99, −1.14

must be 4 K/km. If the electrical conductivity function of the lunar bedrock is in fact similar to that of terrestrial olivines then the Moon is hot with an inferred core temperature of about 1500 °C, while if the bedrock is as electrically conducting as the Apollo 11 crystalline rock considered by Nagata *et al.* (1970) then the Moon is warm with an inferred temperature of ≈800–900 °C. In order for the Moon to be cold, i.e. have a near surface thermal gradient equal to or less than 2 K/km, the lunar bedrock must be even more electrically conducting than considered here.

7. The Permanent Magnetic Field

During the first few days of operation on the lunar surface the Lunar Surface Magnetometer (LSM) disclosed the presence of a permanent magnetic field at the Apollo 12 site [20]. This field has magnitude 38 γ and is directed downwards and in a generally southeasterly direction in the local coordinate system. As part of the initial site survey conducted by the magnetometer upon command from earth, the instrument was operated in a gradiometer mode which determines the horizontal component of the magnetic gradient on the surface. The threshold for this measurement is 10^{-8} G/cm. No gradient in the surface field was detected by LSM. Using this information together with data from orbits of Explorer 35 which passed over the site it is possible to construct an equivalent dipole and to specify limits upon its distance from the LSM and its strength. This dipole lies in the range between 0.2 and 200 km surface distance away and has a strength, p, given by $3\times10^{9} \lesssim p \lesssim 10^{18}$ G cm^3. It is not possible to assess the details of the geometry of the source, but conjecture suggests that the most likely source of the magnetization is due to a fossil residue emplaced in a magma which had cooled through its Curie temperature.

The magnitude of the field is consistent with the paleomagnetism found at both Apollo 11 and 12 sites by direct examination of lunar samples returned to earth [21]. It appears likely that the paleomagnetism is contemporaneous with the Rb/Sr ages found at the sites. These range from 3.2 to 3.7 billion years old, though the possibility remains that other ages lying between the onset of formation and those found so far might appear upon examination of material from other marial sites.

If the source for both the paleomagnetism and the fossil field found by LSM are of generally common origin then both must be explained by a common field of order $10^3\,\gamma$ existing some 1 billion years after the formation of the Moon. There exist several possibilities for the generation of such a source but an additional requirement is that the field be stable for a time required for the magma to cool through its Curie point temperature. Thus it appears unlikely that the interplanetary magnetic field would suffice. First the intensity of the present field would have to be increased by nearly three orders. This requires a combination of enhanced spin and an increase in the field at the Sun, but an increase of the spin rate to wind up the field requires the Sun to have approached the centrifugal limit of stability some 1 billion years after moving onto the main sequence. It seems likely that the solar spin rate experienced its most significant braking prior to 3.5 billion years ago. An equally serious objection arises from consideration of the reversals of the direction of the interplanetary magnetic field known to take place during the solar rotation. These are familiarly known as sector structure and are required in a reasonable model to take place at least twice per rotation in order to conserve the divergence of the field. Such reversals are short episodes compared to the expected cooling time for magma. Even the introduction of a steady component of field normal to the ecliptic raises difficulties since such a field would be swept along by the solar wind as a result of the large electrical conductivity and a strong source of flux would be necessary in the Sun. An alternate would be to suppose that the Sun was endowed with a quadrupole field at the time of the setting of the fossil field, but this is a possibility equally novel as that of the high spin so late in solar evolution.

Other proposals have been made for the insertion of the field such as the impact of meteorites. This would still require the presence of a background magnetic field and merely removes the thermal requirement; in doing so it also removes the age limitations, but it seems as likely that field will be removed by such an impact as inserted, though this cannot be foretold with confidence. An alternate proposal would be for the formation of a plasma cloud associated with the impact of a meteorite to provide the currents necessary for the field generation, but such a field would form after the impact and the energy for freezing the field in would have vanished.

Our opinion is that until suitable laboratory simulations can be performed the most likely candidates for the field source lies either in a planetary dynamo at an early time or a close approach to the Earth. The former requires that the Moon be spinning. Details are obscure; there exist no calculations of the mutual motions of the Earth-Moon system which incorporate the spin angular momentum of the Moon yet it is clear that some spin would have been required. Some idea of the spin rate and the thermal convection needed could be assessed from the magnetic Reynolds number regime which is allowed but this is difficult since it is known from laboratory cases that homopolar dynamos display sudden switch-on properties and these are difficult to predict. Too small a Reynolds number would invalidate a dynamo while too large a value would do likewise for different reasons. Runcorn and Urey have both suggested at different times that the Moon might posses a small core of iron which would not conflict with the overall density provided that the radius were less than 0.2 to 0.3 R_m. However it is not clear that even a metallized interior is required for a dynamo to have operated some 3.5 billion years ago.

The alternate to the dynamo would involve a close approach to Earth with immersion of the Moon in the magnetosphere during the cooling episode of the magma. The catastrophic nature of such an event could be somewhat mitigated by a prograde approach [22] but would indicate that the Moon was a captured body. The onset of a viable Earth chronology at about this time could be explained by such an event; the lunar spin would have been rapidly damped (Peale, priv. comm.) but would not be especially important. The close approach could supply some or all of the basis for breakout of magmatic flows through tidal forces. This is consistent with the formation of the Moon under conditions where accretional heat might have been important, for such heat would be displayed as a peak some several hundred km below the lunar surface after 1 billion years. Nevertheless, such a model must also remain conjectural at the present time and retains certain difficulties having to do with the gross geochemistry of the Moon. In any event these possibilities provide a strong basis for viewing the magnetic discoveries as vital clues which must be incorporated into a viable model for the early history of the Moon.

Note Added in Proof. The electrostatic field shown in Figure 2 is not strictly correct, for the TM mode can be time dependent. Only for the time independent limit is the statement in the figure exact.

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