A New Theory of Lunar Magnetism

Abstract. *In the hypothesis advanced here it is supposed that the field, in which rocks at the lunar surface acquired the remanent magnetization found through the Apollo project, arose from permanent magnetization of the deep interior of the moon. This theory involves the assumption that the moon, apart from a surface shell, accreted cold and remained below the Curie point of iron until sometime later than 3×10^9 years ago. The magnetization was acquired as the moon formed in a gas sphere in the strong magnetic field of the early sun.*

Introduction. One of the most unexpected discoveries of the Apollo program has been that the returned rocks, both crystalline and breccia, possess a stable remanent magnetization (*1*). No present dipole magnetic field larger than 5 γ (1 $\gamma = 10^{-5}$ gauss) has been detected around the moon by the Explorer 35 orbiting satellite. Yet magnetometers landed during the Apollo missions showed that local magnetic fields of up to 300 γ are present. Also, the magnetometers carried in the Apollo 15 and Apollo 16 subsatellites orbiting at heights of about 100 km show complex magnetic anomalies up to 1 γ (*2*). From these observations, it follows that magnetization is widespread in the lunar surface layers and requires the existence of a much stronger magnetic field, of say 1,000 to 10,000 γ, at the time of the formation of these rocks (3.2 to 4.1) $\times 10^9$ years ago.

The origin of this early magnetic field is one of the most intriguing problems of lunar research. The possibility that this field was external to the moon has been discussed and does not appear likely. It might be supposed that the sun at this time had a very much stronger field, but by the dipole formula this would have had to exceed 200,000 gauss at the solar surface—an order of magnitude greater than any yet determined in ordinary stars. A much stronger solar wind magnetic field has been suggested, but this can hardly be expected to possess any steady component along the moon's axis of rotation, which alone remains fixed relative to the rocks being magnetized. An early close approach of the moon to the earth, within a few earth radii, would provide a magnetizing mechanism, but the age of the rocks under consideration extends over 1×10^9 years and the retention of the moon in such a close orbit for so long is dynamically impossible.

Thus, it appears to us that this magnetizing field, present during the time when remanent magnetization was acquired by the surface rocks, must have arisen from within. Hitherto, it has appeared natural to suppose that this field was generated in a molten iron core, by a dynamo process similar to that which is held to account for the geomagnetic field.

A permanently magnetized moon? The possibility that the deep interior of the moon, in its early history, had a strong permanent magnetization which it has since lost does not seem to have been considered. It was, of course, once supposed (*3*) that the earth's main magnetic field arose from the permanent magnetization of its interior due to its ferromagnetic minerals. This idea was discarded long ago. The geothermal gradient places the Curie point isotherm about 25 km deep, and the resultant intensity of magnetization of the crustal rocks (6 emu/cm^3) would have to be many orders of magnitude greater than those observed at the surface. However, by contrast, such an explanation of the moon's ancient magnetic field cannot so easily be excluded. The thermal history of the moon is unknown, but assuming a low-temperature accumulation, neither accretional nor radioactive heating would have raised the temperature of the deep interior to the Curie point during the period 4100 to 3200 million years ago—let alone to the melting point. Thus, the real difficulty with the theory of the core dynamo as an explanation of the natural remanent magnetization of the Apollo samples is that those sources of heat known to have been present seem insufficient to cause differentiation of the entire moon, forming a core and producing a magnetic field, as early as 4100 million years ago. Thus, the alternative view that the deep interior remained so cold, until at least 3200 million years ago, that the Curie point was not exceeded makes the hypothesis of permanent magnetization an attractive one. Of course, in an outer shell, perhaps 200 to 400 km deep (*4*) (of fractional volume f') temperatures were attained so that partial melting and crystallization processes generated the highland material, anorthosite, and the basaltic lavas of the maria.

The dominant magnetic mineral of the Apollo samples is iron, which has both a higher Curie point, 780°C, and a higher saturation magnetization, 1700 emu/cm^3, than the iron oxides that account for the magnetic properties of terrestrial rocks. The saturation remanent magnetization of iron in single domain form is 850 emu/cm^3 and in a multidomain state it is less. Suppose iron particles are disseminated throughout the moon (to an average volume concentration f) and are magnetized to intensity I. Then, if the magnetization is uniform in magnitude and direction, the field at the pole will be $(8\pi/3)(1 - f')fI$. If we suppose f is 0.1 percent, then the required field of 1000 γ can be obtained if $I = 1$ emu/cm^3, a strength easily acquired by iron, being a fraction of 1 percent of its remanence. Or, to look at the matter from another point of view, the average intensity of magnetization of the moon must be 4×10^{-4} emu/g: this is not much greater than the magnetizations observed in lunar rocks.

It is perfectly natural for this permanent magnetization of the deep interior to disappear, for meteoritic amounts of disseminated radioactivity would heat the interior up to above the Curie point of iron in the later period of lunar history (*5*). In fact, it would require the assumption of a much lower concentration of radioactivity than is found in meteorites to produce a thermal history which would not do so. Convection would cool the moon's interior, but the solid-state creep process which allows this to occur in a solid would only become important above the Curie point. In any case, convection would disorientate the magnetization were it to occur below the Curie point.

Origin of the moon. This hypothesis presupposes that the moon formed by accretion from a solar nebula of gas and dust which broke up into separate spheres of gas, one of which became the moon (*6*). In this self-gravitating body settling of the solids occurred. When the radius of the gas sphere was large, temperatures of the deep interior were low. As the sphere contracted, temperatures rose (*7*) and the final materials to settle were probably in a hot or even melted condition; thus, an outer molten shell with a cold interior would be produced.

The pressure-temperature histories of such spheres have been calculated and reported by Bainbridge (*8*) and Ostic (*9*). They used observed equations of state for mixtures of hydrogen and helium and showed that the presence of a lunar mass in the center made little difference in the calculated quantities. Emden gas spheres are satisfactory for low pressures and temperatures and for the larger radii. As Bainbridge points out, settling of solids should occur at low temperatures when the sphere is large and volatiles would be retained, but as the sphere contracts, temperatures would rise and volatiles would be removed and should be missing from the outer parts of the solid body. This last feature is obviously what is observed on the moon; but as yet, we cannot say whether the interior contains the volatiles, which she suggests as a possibility, although the work of Middlehurst (*10*) on lunar transient events strongly suggests the escape of such volatiles. Of course, if all settling occurred at high temperatures, the volatiles would be missing throughout.

Mechanism of original magnetization. We return now to a discussion of possible mechanisms by which this uniform magnetization of the early moon was acquired. This is, of course, highly speculative, but strong magnetic fields in the early solar system have been postulated to account for its angular momentum distribution (*11*). Moreover, the remanent magnetization found in meteorites seems to be evidence for such an early magnetic field (*12*). The rotating, flattened primeval cloud of dust and gas contracted to form the sun, leaving a nebula from which the planetary bodies accreted. Assuming the existence of a tenuous magnetic field in the primeval disk, this field would be trapped and increased in regions where the gas contracted and in particular around the forming moon.

Supposing that the field of the dust cloud is of similar strength to the galactic field (that is, 10^{-5} to 10^{-6} gauss) and that its initial radius is about 50,000 A.U., contraction to about 1 A.U. would increase its field to 2,000 gauss if no lines escaped, although this is unlikely. Gravitational instability and probably other effects result in the breaking off of gas spheres, which would retain some part of this magnetic field. If we assume a gas sphere with a radius of 400,000 km and an electrical conductivity of σ ohm/cm, the free decay time of such a field would be $5\ \sigma \times 10^4$ years. The value of σ for such a cold gas would depend on its weak radioactivity: this is difficult to calculate but could hardly be greater than 1. Consequently, the magnetic field of the gas sphere itself would probably not be retained for a sufficient length of time unless the settling process takes place exceedingly rapidly or dynamo action occurs in this rapidly rotating envelope. We thus conclude that the magnetizing field comes from the sun itself. When the sun's radius has contracted to about 0.1 A.U., it would be similar to a B-type star: these have been shown to possess surface magnetic fields of 20,000 gauss, and at 1 A.U., by the dipole relation, would produce 20 gauss, about that required by our hypothesis. If such a vast gas sphere possessed a magnetic field, the geometry of lines of force near its center where the lunar body would be located, would have to be uniform and directed along the axis of rotation. Thus, if the iron was uniformly disseminated, the resulting field when the gas sphere was removed, possibly during the T Tauri phase of solar evolution, would be dipolar.

There are few possible ways in which rocks can and the lunar interior could be magnetized.

1) A strong field applied momentarily produces an isothermal remanent magnetization. Laboratory experiments on lunar rocks can be used as a guide to estimate the strength of the magnetizing field required. A field of about 10 gauss is needed.

2) A weak field applied for a long time produces a viscous remanent magnetization. The intensity increases logarithmically with time. After the removal of the field, the intensity decays with a similar time scale.

3) Small magnetized particles depositing in a nonturbulent fluid orient themselves in an ambient magnetic field, and on forming and consolidating into a sediment give a magnetic moment to the material. This "depositional" magnetization might occur if the particles were small and were falling in a gas sphere in a quiet state.

4) In the familiar thermoremanent magnetization the rock cools from above the Curie point to a low temperature in a weak magnetic field.

The sequence of temperature changes in the deeper parts of the moon required to produce the thermoremanent magnetization described under method 4 seems very difficult to arrange. A viscous remanent magnetization produced in a gas sphere that might exist for only tens of millions of years seems unlikely to be retained until as late after the formation of the moon as is required to explain the magnetization of rocks 3200 million years old. However, methods 1 and 3 could possibly occur during the formation of a cold body. Magnetization method 3 could occur in a gas sphere produced in the solar nebula by gravitational instability, as proposed some years ago (*6*).

Our suggestion that sediment settling in a gas sphere in the presence of a primeval magnetic field accounts for a temporary lunar magnetic field (4.6 to 3.2) $\times 10^9$ years ago requires that the initial settling took place at low temperatures. In this case, the gas sphere model accounts exactly for the discussion of the magnetic fields presented in this report.

Possible tests of the hypothesis. As we have no reason to suppose that the dynamo in a small lunar core would produce a field other than that of an axial dipole, which is also that of a uniformly magnetized sphere, no test between the theories is likely through observations of the directions of magnetization of rocks from different latitudes. From an extensive subsatellite magnetic survey of the moon, it may eventually be possible to infer the directions of magnetization of rock units of different ages. It may be possible to determine two types of information from such a study. (i) Reversals of polarity of the magnetization at different times, if these have occurred, should be detected. Such reversals would be explainable by the core dynamo hypothesis, and would exclude the hypothesis put forward in this report. (ii) The approximate time when the magnetic field disappears and its change with time might be found. An increase of the field with time would rule out our hypothesis.

Laboratory studies on rocks of different ages also yield determinations of the intensity of the field at different times. An increase or large fluctuation in the field would be incompatible with the hypothesis we are advancing.

Of course, if other evidence relating to the temperature of formation of the moon could be found or if electrical heating of the early moon by the strong solar wind of the T Tauri phase of the sun's evolution (*13*) could be invoked with certainty then the existence of an early dynamo might again become attractive. Or if the existence of an iron core, so far only inferred from a convective theory of the nonhydrostatic figure of the moon (*14*), becomes more decisive, the questions raised in this report will receive a definite answer.

S. K. RUNCORN
Lunar Science Institute,
Houston, Texas 77058, and
Department of Geophysics and Planetary Physics, School of Physics, University of Newcastle upon Tyne, Newcastle upon Tyne NE1, 7RU England
H. C. UREY
Department of Chemistry, University of California, San Diego, La Jolla 92037

References

1. S. K. Runcorn *et al.*, *Geochim. Cosmochim. Acta* **3** (Suppl. 1), 2369 (1970); *Proc. Roy. Soc. London Ser. A* **325**, 157 (1971); C. E. Helsley, *Geochim. Cosmochim. Acta* **3** (Suppl. 1), 2213 (1970); T. Nagala, R. M. Fisher, F. C. Schwerer, M. D. Fuller, J. R. Dunn, *ibid.* **3** (Suppl. 2), 2461 (1971); D. W. Strangway, G. W. Pearce, E. Larsen, *ibid.* **3** (Suppl. 1), 2435 (1970).
2. P. J. Coleman, G. Schubert, C. T. Russell, L. R. Sharp, *Moon* **4**, 419 (1972); P. Dyal, C. W. Parkin, C. P. Sonett, *Science* **169**, 762 (1970); J. D. Michalov, C. P. Sonett, J. H. Brinscak, M. D. Moutsoulas, *ibid.* **171**, 892 (1971).
3. S. Chapman and J. Bartels, *Geomagnetism* (Oxford Univ. Press, London, 1940).
4. H. C. Urey, K. Marti, J. W. Hawkins, M. K. Liu, *Proceedings of the Second Lunar Science Conference*, A. A. Levinson, Ed. (M.I.T. Press, Cambridge, Mass., 1971), vol. 2, pp. 987–998.
5. H. C. Urey, *The Planets* (Yale Univ. Press, New Haven, Conn., 1952).
6. ———, *Mon. Not. Roy. Astron. Soc.* **131**, 199 (1966).
7. A. S. Eddington, *Internal Constitution of the Stars* (Cambridge Univ. Press, London, ed. 3, 1930).
8. J. Bainbridge, *Astrophys. J.* **136**, 202 (1962).
9. R. G. Ostic, *Mon. Not. Roy. Astron. Soc.* **131**, 191 (1965).
10. B. M. Middlehurst, in *The Moon*, S. K. Runcorn and H. C. Urey, Eds. (Reidel, Dordrecht, Netherlands, 1972), pp. 450–457.
11. H. Alfven, *On the Origin of the Solar System* (Clarendon Press, Oxford, 1954).
12. S. K. Runcorn, in *From Plasma to Planet, Nobel Symposium 21*, A. Elvius, Ed. (Almqvist & Wiksell, Stockholm, 1972), pp. 373–376.
13. C. P. Sonnett, D. S. Colburn, K. Schwartz, *Nature* **219**, 924 (1968).
14. S. K. Runcorn, *Proc. Roy. Soc. Ser. A* **296**, 270 (1967).

15 March 1973

■

Periodic Insolation Variations on Mars

Abstract. *Previously unrecognized insolation variations on Mars are a consequence of periodic variations in eccentricity, first established by the theory of Brouwer and Van Woerkom (1950). Such annual insolation variations, characterized by both 95,000-year and 2,000,000-year periodicities, may actually be recorded in newly discovered layered deposits in the polar regions of Mars. An additional north-south variation in seasonal insolation, but not average annual insolation, exists with 51,000-year and 2,000,000-year periodicities.*

Unique layered deposits have been discovered in the polar regions of Mars through Mariner 9 photography (*1*, *2*). A history of periodic entrapment, by solid CO_2 deposits on the surface, of dust particles settling out from planet-wide dust storms is likely recorded there. Murray *et al.* (*1*) postulate that the individual layers might be associated with a 50,000-year alternation in the pattern of insolation at the two poles of Mars previously recognized by Leighton and Murray (*3*). A longer-period effect in depositional conditions is indicated by the association of tens of individual layers into distinct overlapping plates. This longer-period effect was ascribed to some unrecognized climatic fluctuation by Murray *et al.* (*1*).

We report here previously unrecognized long-term periodic variations in the solar insolation reaching Mars (*4*), which can be expected to regulate the growth and disappearance of perennial CO_2 deposits and probably also the production of planet-wide dust storms. These insolation variations arise from variations in the eccentricity of the orbit of Mars. This pattern of insolation variations bears a striking similarity to the long-period and short-period fluctuations that seem to be recorded by the layered deposits. Thus, we propose that this newly recognized long-term periodic variation in the insolation, arising from a periodic fluctuation in the eccentricity of the orbit, may be recorded in the polar regions of Mars. A later paper (*5*) will outline considerations of the actual mechanisms by which this process may have taken place.

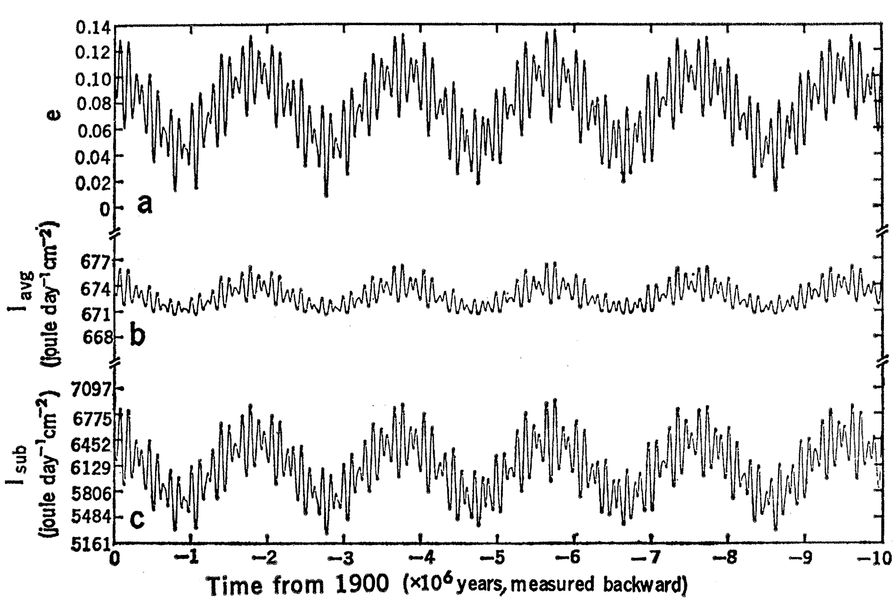

Fig. 1. (a) Eccentricity of Mars for the past 10^7 years; (b) average annual insolation at the poles; (c) insolation at the subpolar point at perihelion.

Long-term changes in the eccentricity of the orbit of a planet can be computed by using the Laplace-Lagrange theory of secular perturbations. The disturbing function is limited to its secular part; that is, all periodic terms containing the mean longitudes are ignored. This is equivalent to spreading out the mass of each planet in the solar system along its orbit with a local density proportional to the time spent at each position. Since the eccentricities can sometimes become very small, it is convenient to define the following quantities: $h_i = e_i \sin\omega_i$, $k_i = e_i \cos\omega_i$, where e_i and ω_i are the eccentricity and longitude of perihelion, respectively. The pertinent part of the secular disturbing function between two planets p and q thus takes the form

$$\bar{R}_{pq} = \frac{GM^* a_p}{4a_q^2}\left[\tfrac{1}{2} b_{3/2}^{(1)}(h_p^2 + k_p^2 + h_q^2 + k_q^2) - b_{3/2}^{(2)}(h_p h_q + k_p k_q)\right] \quad (1)$$

and the perturbation equations for h_i and k_i are

$$\frac{dh_i}{dt} = \frac{1}{n_i a_i^2}\frac{\partial \bar{R}_i}{\partial k_i} \qquad \frac{dk_i}{dt} = \frac{-1}{n_i a_i^2}\frac{\partial \bar{R}_i}{\partial h_i} \quad (2)$$

where $\bar{R}_i$ is the total secular disturbing function felt by planet i obtained by summing the contributions from all the other planets, n_i is the mean motion, and t is time. In Eq. 1, G is the gravitational constant; a_p and a_q are the semimajor axes, with $a_p < a_q$; and $b_s^{(r)}$ denotes a Laplace coefficient that is a function of a_p/a_q. The mass of the perturbing object is denoted by M^*. Carrying out the differentiation indicated in Eq. 2 yields a system of linear first-order differential equations. The motions of the perihelia and changes in the eccentricities of all the planets are coupled to each other and must be solved for together. A solution has been obtained for the solar system (excluding Pluto) by Brouwer and Van Woerkom