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The Ancient Lunar Core Dynamo

Abstract. *Lunar paleomagnetism provides evidence for the existence of an ancient lunar magnetic field generated in an iron core. Paleointensity experiments give a surface field of 1.3 gauss, 4.0 × 10⁹ years ago, subsequently decreasing exponentially. Thermodynamic arguments give a minimum value of the heat source in the core at that time: known sources, radioactive and other, are quantitatively implausible, and it is suggested that superheavy elements were present in the early moon.*

Igneous rocks and high-grade breccia returned from the moon by the Apollo project possess natural remanent magnetization (NRM) with a stability similar to that of terrestrial rocks (*1*). This paleomagnetism has been interpreted as a thermoremanent magnetization (TRM) acquired at the original extrusion and crystallization of the lavas between 4.0 and 3.2×10^9 years ago (*2*) and at the cooling of the breccias during their formation. Lunar magnetic anomalies have been mapped at an altitude of 100 km by subsatellite magnetometers (*3*) and at the surface both by magnetometers and by low-energy electron reflections (*4*). These anomalies have magnitudes and scales such that they evidently arise from this remanent magnetization of crustal rocks. Surprisingly, the present dipole moment arising from the magnetized outer shell is negligible (*5*), but from this null result I conclude that the moon once possessed a magnetic field that was generated in its interior and was responsible for magnetizing the rocks (*6*). This field has now disappeared. Paleointensity determinations have been made on Apollo rocks by two methods. In the Thellier-Thellier method, the rock is heated to successively higher temperatures in a zero field so as to remove the NRM stepwise, and a comparison is made with a similar stepwise acquisition of a TRM as the rock is cooled from above the Curie point in a small laboratory magnetic field. In an analogous method, strong alternating magnetic fields replace temperature in its effect on domains. The results have been interpreted as showing that the magnetizing field in which the rocks acquired their TRM decreased exponentially from 1.3 gauss at 4.0×10^9 years ago to 5000 γ ($1\ \gamma = 10^{-5}$ gauss) 3.2×10^9 years ago (*7*). Thus, although explanations of lunar paleomagnetism caused by the impact of meteorites or comets are being examined (*8*), this relation between paleointensity and age argues in favor of the existence of an ancient lunar field.

The source of this lunar field of internal origin is a key question with respect to the structure and thermal history of the early moon. An origin consistent with a uniformly accreted and initially cold moon, the deep interior remaining below the Curie point of iron for the first 1 to 1.5×10^9 years, was suggested (*9*). As the moon accreted, it acquired a uniform permanent magnetization from a solar system magnetic field retained in the solar nebula after its formation: its deep interior remained magnetized, although diminishingly so because of radioactive heating, until after the youngest lava samples examined had been extruded. This theory is no longer tenable on quantitative grounds as a result of the paleointensity determinations (*10*). According to the alternative theory, the moon has an iron core which was fluid in its early history and generated a field by a dynamo process. The absence of a field today is explained if the core either solidified or ceased dynamo action because the magnetic Reynolds number became subcritical in the time since 3.2×10^9 years ago (*1*). I inferred the existence of an iron core (*11*) on entirely different grounds: if creep occurs, the moon's nonhydrostatic figure must result from a second-degree harmonic convection current in its solid silicate mantle. But direct evidence for the existence of the core based on seismic signals (*12*) or electrical conductivity determinations (*13*) is, at present, only suggestive. However, the latest value (*14*) of the moment of inertia factor C/Ma^2, where C is the polar moment of inertia, M is the mass, and a is the radius, is 0.391 ± 0.002. This value is not consistent with differentiated outer shells over an otherwise uniformly dense moon, for I have shown (*15*) that these outer shells would reduce C/Ma^2 by only about 0.002 below the value of 0.4 for a uniform moon. In fact, the mean value of C/Ma^2 given above would allow the existence of a lunar core of radius $b = 500$ km. I will use this radius.

Suppose that an iron core exists within the moon and that it was molten (that is, at 1900°K) at least between 4.0 and 3.2×10^9 years ago. Thermodynamic arguments may now be applied to the core (if we think of it as a heat engine) in which a yet unknown heat source (E) within it drives convective motions which generate the dipole field. I use an argument applied by Gubbins (*16*) and Backus (*17*) to the geomagnetic dynamo, although for the case of the earth's core no critical conclusions emerge. The dipole field (H_0 at the core surface on the lunar equator) arises from a toroidal, second-degree harmonic, electric current distribution over concentric spherical surfaces within the core with an unknown radial distribution. The latter, however, can be chosen, to give a minimum ohmic dissipation P in the core, which equals $30\ b\ H_0^2/4\ \pi\sigma$, where σ is the electrical conductivity of molten iron (7.4×10^3 ohm^{-1} cm^{-1}) (*16*). The ratio of "useful" work done by the dynamo (that which is essential to the field generation) to the heat source driving it, P/E, is not greater than a quantity of similar form to the Carnot efficiency, that is, $k\Delta T/T$, where T is the temperature at the outside of the core and ΔT is the actual difference in temperature between the center and the surface of the core. The difference from the Carnot cycle arises as the work done in this heat engine is fed into the convecting system as heat, but no case where $k > 1$ has been found. I assume that $k = 1$ if the heat source is at the center and $k = 2/5$ if the heat source is uniformly distributed through the core (*18*). On such a scale, the superadiabatic gradient necessary for convection is very much less than the adiabatic gradient and thus makes a negligible contribution to ΔT. The adiabatic gradient is $\alpha gT/C_p$ where α is the volume coefficient of expansion of molten iron (12.2×10^{-5} per degree Celsius), g is the gravitational acceleration (98 cm sec^{-2} at the core surface), and C_p is the specific heat of iron per unit mass. Thus $P/E \leq (2/5)(75/1900) = 0.016$ for a uniformly distributed heat source, which is the most plausible case.

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If the paleofield measured is an equatorial field, $H_0 = 55$ gauss and $P = 4.8 \times 10^9$ watts at 4.0×10^9 years ago. The actual ohmic heat dissipated in the core will be considerably greater as no allowance has been made for the toroidal magnetic field, an essential part of the dynamo process, which may be 1 to 100 times the strength of the poloidal field: a very conservative estimate would be that P is trebled. Thus the absolute minimum value of E is 10^{12} watts. The heat flow out of the core 4.0×10^9 years ago, the surface area being 3×10^{16} cm^2, was 0.3×10^{-4} watt cm^{-2}. Assuming that there are no heat sources in the mantle but that it convects so that a thermal equilibrium is always maintained within the moon, the heat flow out of the moon's surface 4×10^9 years ago would have been 0.25×10^{-5} watt cm^{-2} as compared with 1.8×10^{-6} watt cm^{-2} at present. The radioactive heat sources in rocks (^{238}U, ^{235}U, Th, and ^{40}K) were greater 4×10^9 years ago than they are today by factors of 1.85, 47, 7.2, and 9.2, respectively, but uranium and thorium do not dissolve in iron. The discussion of the presence of potassium in the iron core is a complex chemical question. Potassium does not dissolve under ordinary circumstances in pure iron, but a number of workers have suggested that the lunar core may be an iron–iron sulfide eutectic (*19*). The experimental data on this matter are still controversial, but it would appear that only a small percentage of the potassium in the moon could be carried down to the iron core at the relatively low pressures in the moon, whereas in the earth the very high pressures introduce an element of doubt into the interpretation of the low-pressure observations. If the moon's composition is that of carbonaceous chrondrites and the potassium is wholly within the iron core, the heat generation within it would be about 1.5×10^{11} watts today and 1.4×10^{12} watts 4×10^9 years ago, a little more than is required on the basis of the above assumptions. However, the value of P required is the absolute minimum and that available is the maximum available on the basis of the unrealistic hypothesis that all the ^{40}K is in the core. I conclude that the driving of the dynamo to produce the fields inferred 4×10^9 years ago presents a serious difficulty with respect to current ideas.

What other sources of heat are available to drive the lunar dynamo? In its early history, the moon's spin decreased and the rotational energy lost would have been dissipated within the moon. If the moon were once rotating with a period of 24 hours, its rotational energy would have been 2.4×10^{26} joules, and, if this energy were dissipated over 10^9 years, the power available for driving the dynamo would be 7.6×10^9 watts, although it would equal the minimum P if the moon reached synchronous rotation in 7.6×10^6 years. In fact, most of the energy would have been dissipated in the mantle and would not have been available to drive the core dynamo.

Another idea is that the core cooled, through heat extracted from it by convection in the silicate mantle, and this cooling drove convection in the core. Then 4×10^9 years ago, the temperature of the core would have had to be falling at a rate of 1°C per 10^4 years, and the high field could not have existed for long. Or it may be supposed that the core is solidifying from the center outward, releasing latent heat to drive convection in the outer core. The total heat released when one half of the core has solidified is 5×10^{26} joules. This amount of heat would run the dynamo for only 32×10^6 years. The formation of the core from an undifferentiated moon would also release energy, although most of the gravitational energy would be released in the silicate mantle as the iron falls through it. A rate of growth of the core of about 4 km year^{-1} would be required to run the dynamo.

The above arguments point strongly to the existence in the moon in its first few hundred million years of an energy source an order of magnitude greater than that anticipated on the basis of present knowledge. It has recently been tentatively suggested (*20*) that superheavy elements in the "island of stability" of atomic number between about 116 and 124 might have been present in sufficient concentration to dominate the early thermal history of the moon. The searches for the existence today of such superheavy nuclei in monazite crystal inclusions in Precambrian micas are inconclusive. These inclusions within the giant halos (*21*) have been irradiated by protons and x-rays (*22*) to excite the x-ray lines of the superheavy elements but with contradictory results. A new explanation of the giant halos by knock-on protons in water has been suggested (*23*), but the presence of the necessary water is thought to be unlikely (*20*). In carbonaceous chondritic meteorites spontaneous fission of nuclei has been observed with the ejection of four to ten neutrons (*24*). But it has long been believed on theoretical grounds that nuclei with such atomic numbers might have relatively long half-lives. To be relevant to this problem, their half-lives must be 10^8 to 10^9 years. Consequently, the concentrations of these nuclei in any terrestrial or extraterrestrial samples available today may be below the threshold of detection. Even so, they may still have been of great significance in the early history of the moon not only as the heat source which caused complete differentiation of the moon (*20*) about 4.4×10^9 years ago, but also as the source of the energy for driving the dynamo so vigorously 4.0×10^9 years ago.

After the discovery of the ^{26}Mg anomaly in the Allende meteorite, Lee *et al.* (*25*) argued that ^{26}Al had been present in the early solar system. Because of its abundance, this ^{26}Al would have been a very adequate heat source for melting planetary bodies, provided that both the interval of time between the end of nuclear genesis and the formation of solar system nebula and the time taken for lunar-sized bodies to accrete were not great compared to the half-life (730×10^3 years). It has been argued that the former time is likely to have been about 10^8 years (*26*), and the latter time also seems likely to be of the same magnitude (*27*) although 10^6 years has been suggested (*28*). The role of ^{26}Al as a heat source in the early solar system is a matter on which a conclusive decision is difficult. But, the present argument does not depend on eliminating ^{26}Al as an important early heat source in the moon: it is clearly impossible chemically to have had appreciable quantities of aluminum in the iron core.

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Isostasy in Australia and the Evolution of the Compensation Mechanism

Abstract. *A linear transfer function analysis has been applied to gravity and topographic data from Australia to calculate the isostatic response function of Dorman and Lewis. The Australian response function is considerably different from that calculated for the United States. The differences can be explained on the basis of an apparent evolution of the isostatic compensation mechanism in which viscoelastic creep occurs in the lithosphere and relaxes the initial long-wavelength elastic stresses.*

It has been known for over a century that the measured gravitational field over mountainous regions is less than one would predict if the elevated masses simply rest upon a laterally uniform earth. Pratt (*1*) and Airy (*2*) independently proposed that low-density material buoying up the topography was responsible for the reduced attraction, and this idea is still accepted today. The adjustment of density at depth corresponding to surface elevation is called isostasy. Dorman and Lewis (*3*) undertook a systematic investigation of isostatic compensation at long length scales by calculating the linear transfer function relating the measured Bouguer anomaly to land elevation. They assumed that

$$\Delta g_B(\mathbf{r}_0) = \int_S q(|\mathbf{r}_0 - \mathbf{r}|)\, h(\mathbf{r})\, ds + n \qquad (1)$$
$$= q * h + n$$

Here $\mathbf{r}_0$ and $\mathbf{r}$ are position vectors in a standard equipotential surface (sea level), Δg_B is the Bouguer anomaly (the residual gravitational field after removal of the main field and the attraction of the elevated masses), $h(\mathbf{r})$ is the land height above sea level at $\mathbf{r}$, and q is an unknown function; n represents gravity anomalies not caused by isostatic compensation. The form of Eq. 1 is based upon the plausible assumption that the isostatic compensation of a point load would cause symmetrical density anomalies beneath it. If the isostatic gravity anomalies, $q * h$, are uncorrelated with n, we may recover the function q from measurements of Δg_B and h. This is best accomplished in the wave-number domain because, if the earth's curvature is neglected (*4*), Eq. 1 can be Fourier-transformed to give

$$\Delta G_B(\mathbf{k}) = Q(|\mathbf{k}|)\, H(\mathbf{k}) + N \qquad (2)$$

In Eq. 2 uppercase variables denote two-dimensional Fourier transforms of lowercase variables, $\mathbf{k}$ is the horizontal wave number, and Q is called the isostatic response function. Dorman and Lewis analyzed gravity and topographic data from the continental United States. They showed that the linear model is satisfactory and that nonlinear terms are not required.

We report here the results of our application of the linear transfer function analysis to measurements covering Australia. We chose Australia because the crust there is, on the average, considerably older geologically than that in the United States. We hoped to see evidence in Q that the cool thick lithosphere of the more mature Australian continent is more rigid than that of the younger United States; this difference was suggested by Molnar and Tapponnier (*5*) to explain the comparative lack of deformation of India as it pushes into Asia. The Australian Bureau of Mineral Resources gave us access to over 200,000 gravity and land elevation measurements extending over the entire Australian continent. We removed from the gravity data a background field computed from the satellite-determined (*6*) spherical harmonic representation of the earth's gravity field up to the 16th degree (Goddard Earth model 7). The masses causing this field are assumed to be too deep to be involved in isostasy. We computed the terrain correction by subtracting out the attraction of a slab with a density of 2670 kg m^{-3} and a thickness equal to the station elevation. Fraser *et al.* (*7*) showed that the errors from this approximation are quite small because of the rather subdued topography in Australia.

Figure 1 shows the response function we obtained for Australia and that of Dorman and Lewis for the United States. The uncertainty in the estimates is caused by gravity anomalies uncorrelated with topography. The two isostatic response functions evidently agree at the longest and shortest wavelengths, but in the roll-off region where wavelength (λ) = 500 km, the Australian response is consistently lower.

To understand what this difference signifies, we turn to a model of isostatic compensation. Dorman and Lewis (*8*) interpreted their response function in terms of a local linear mechanism: here a density anomaly occurs only directly beneath the elevated region with which it is associated, and the amplitude of the density anomaly is linearly proportional to the elevation. Banks *et al.* (*9*) considered this model to be untenable because density increases as well as decreases are required to fit Q for the United States. They suggested that the positive density anomalies are artifacts of the assumption of local compensation and that another model in which the density anomalies are distributed horizontally as well as vertically is more plausible. In this model, the lithosphere is represented by a thin elastic slab with internal density gradients, resting on a homogeneous fluid mantle. When a topographic load is applied, buoyancy forces from the fluid support it, but the elastic slab distributes the deflection over a wide area; this is called a regional compensation model. Applied to the Q function for the United States, this model yields values for D, the flexural rigidity of the slab, in the range 10^{21} to 10^{22} newton-m. There is a discrepancy between Walcott's (*10*) values, 3×10^{22} to 6×10^{23} newton-m, and those of Banks *et al.* (*9*) derived from an analysis of the same data. The difference is due to the use of the slab approximation in Walcott's calculation of the gravitational attraction from the deformed sheet; at all wavelengths of interest, this approximation results in a serious overestimate of D.

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