Reports

Magnetic Dynamo in the Moon: A Comparison with the Earth

Abstract. *The assumption that the moon had an internal magnetic field produced in the same way as the geomagnetic field requires that the moon rotated faster than the angular velocity at which it would break up. This suggests that a lunar dynamo is not a tenable explanation for the magnetic remanence observed on the moon.*

The identification of remanent magnetism in lunar rock samples (*1, 2*) returned to the earth through the Apollo missions and the possibility that the moon's crust has a residual magnetic field (*3*) have prompted speculation that the moon had an internal magnetic field during part of its history (*2*). It is believed that magnetic fields in planetary bodies are the result of self-excited hydromagnetic dynamos in the electrically conducting liquid cores of these bodies. The efficient production of a magnetic field in a planetary body seems to require that the body rotates and that its core overturns convectively. Thus, it is widely recognized that the prior existence of a lunar dynamo magnetic field implies that the moon has a conducting core (presumably made of iron) which was at one time molten and convecting and that the moon rotated faster in the past than it does today. In this report we explore quantitatively the suggestion (*2*) that thermal convection in the core of a rotating moon produced a magnetic field.

A theoretical discussion of planetary dynamos is hindered because we have little empirical knowledge of the fluid motions within the cores of such bodies and because there is no adequate theory of the convection of a fluid sphere heated within. The one planetary dynamo that we have any direct experience with is the one in the earth. The approach we take here is to assume that a dynamo magnetic field in the moon would be produced in the same way that the earth's magnetic field is believed to be produced. Then, knowing that the criterion for the production of such a magnetic field admits a scaling relation and making simple arguments about the effect of the Coriolis force on the fluid motions, we derive a relation between the rotational angular velocity of the earth and the rate of rotation of the moon that would be necessary to produce an analogous lunar magnetic field.

There are several ways to derive the equations describing a planetary dynamo (*4, 5*). Parker's derivation (*5*) is the most transparent physically, and we use the equations in the form that he obtained. Solving these equations for a stationary magnetic field in a rotating spherical body (*6, 7*), we find that the criterion for the production of a magnetic field is that the dynamo number,

$$N \equiv \frac{l^3 \Gamma \gamma}{\eta^2}$$

takes a value which we term the critical dynamo number, N_c. In this equation, l is the length characterizing the size of the dynamo region, here the radius of the conducting core; γ is the rate of nonuniform rotation, $\gamma = (\partial u_\phi / \partial r - u_\phi / r)$, where u_ϕ is the rotational velocity of the fluid core and r is the radial coordinate; and η is the magnetic diffusivity. In order of magnitude,

$$\Gamma = \nu u_r u_c \lambda^2 (\delta t)^2$$

where u_r and u_c are, respectively, the radial and cyclonic components of the convection, δt is the lifetime of a convective cell, λ is its characteristic size, and ν is the rate of appearance of cells of cyclonic convection (*8*). In a fluid that is convecting throughout, ν is equal to $1/\lambda^3 \delta t$.

Now consider the gross effect of the Coriolis force on the fluid motions. In a body that rotates with angular velocity Ω, u_c is proportional to $\lambda\Omega$; we will assume that the constant of proportionality is the same for the moon as for the earth. The lifetime of a turbulent convective cell, δt, is approximately the time that it takes the fluid to traverse the core (*9*), that is, $u_r \delta t$ is about equal to l. Taken together, these arguments yield Γ proportional to $l\Omega$. The nonuniform rotation is also due to the Coriolis force, and since γ is the derivative of the rotation rate we write $\gamma \propto \Omega$, where again we assume that the constant of proportionality is the same as for the earth. Then for the dynamo number of a rotating and convecting sphere of conducting fluid we have

$$N \propto \frac{l^4 \Omega^2}{\eta^2} \qquad (1)$$

with the constant of proportionality the same in the (presumed) formerly liquid iron core of the moon as in the present liquid iron core of the earth.

The dynamo number expresses the ratio of the rate of production of electrical currents, by the Lorentz force of the fluid velocity and the magnetic field, to the rate of dissipation of electrical currents by resistive heating. If the fluid motion is not sufficiently vigorous to produce currents as rapidly as they are dissipated, then no magnetic field is maintained; this corresponds to N less than N_c. If the fluid motion is so vigorous that the currents are produced more rapidly than they dissipate, the magnetic field grows in amplitude; in this case N is greater than N_c. A stationary magnetic field—one which exists over a long period of time with a constant amplitude—arises when the rate of production of electrical currents equals the rate of dissipation. This equality is expressed by N equals N_c. The geomagnetic field is known, from paleomagnetic evidence, to fluctuate about a stationary mean of 0.5 gauss (at the equator). Thus, in the earth, N equals N_c.

The critical dynamo number, N_c, is independent of the dimensions of the dynamo region and depends only on the (dimensionless) geometrical distribution of nonuniform rotation and cyclonic convection. We will assume, as a working hypothesis, that the convection is distributed over the liquid metal core of the moon, as it is over the core of the earth (*10*). Then for corresponding states of the magnetic field $(N_c)_M$ is equal to $(N_c)_E$, where M and E stand for moon and earth. The observed mass and moment of inertia of the moon place an upper limit of 20 percent of the lunar radius, or 350 km, on the radius of an iron core in the moon; that is, $l_E \geqslant 10 l_M$. Altogether, for corresponding states of the magnetic field

$$\left(\frac{\Omega_M}{\Omega_E}\right)^2 \geqslant 10^4 \qquad (2)$$

where, for the purpose of the argument, we have assumed that the electrical conductivity of the lunar core is the same as that of the earth's core (*11*) and that both dynamos operate in the same state. In the core of the earth, the dynamo is probably operating in its most easily excited dipole state or in its second most easily excited dipole state [the higher states are so unstable that they would reverse more often than the geomagnetic field is known to (*7*)]. We make the conservative assumption that a lunar dynamo operated in its most easily excited state. Then, if the earth's dynamo operates in its lowest state, Eq. 2 stands as it is; if it operates in its second lowest state the right hand side of Eq. 2 is diminished by a factor of 10 (*7*).

Therefore, this comparison implies that $\Omega_M \geqslant 100\Omega_E$ (or $\Omega_M \geqslant 30\Omega_E$ if the geomagnetic dynamo is in its second lowest state) if the moon had an internal magnetic field produced in the same way as the earth's. This lunar rotation period of approximately 15 minutes (or 45 minutes) is smaller than the rotation period of about 80 minutes at which the moon would break up.

To conclude, the assumption that the moon had a dynamo magnetic field produced in the same way as the earth's magnetic field requires that the moon rotated excessively fast, faster than its breakup angular velocity. While this crude kinematic (*12*) analysis cannot definitely rule out the possibility that the moon had an internal dynamo (for example, with our lack of knowledge of the properties of a lunar core and, in fact, of the earth's core, there may be some crucial difference between the two) it casts serious doubt on that possibility, even granting that the moon had a molten iron core. In view of this and of the geochemical objections against a molten iron core in the early moon, we suggest that the search for alternate mechanisms to account for the magnetic properties of the moon not be abandoned.

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References and Notes

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6. E. H. Levy, *ibid.* **171**, 621 (1972).
7. ———, *ibid.* **175**, 573 (1972).
8. E. N. Parker, *ibid.* **163**, 255 (1971).
9. Secular variations in the surface geomagnetic field indicate that this is, in fact, the case for the earth.
10. The secular variation of the geomagnetic field reflects the fluid motions in the core of the earth. See W. M. Elsasser, *Rev. Mod. Phys.* **22**, 1 (1950).
11. If we do not assume equal conductivities, Eq. 2 becomes $(\Omega_M/\Omega_E)^2 \geqq 10^4\ (\sigma_E/\sigma_M)^2$, where σ is the electrical conductivity of the core.
12. In the kinematic analysis the origin of the fluid motions is not explicitly discussed. In particular, we have not addressed ourselves here to (the unsolved problem of) the inhibition of the fluid motion by the magnetic forces themselves.
13. I thank D. G. Wentzel and H. Frey for stimulating discussions about the moon.

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Phosphorescence of Adsorbed Ionic Organic Molecules at Room Temperature

Abstract. *Many salts of polynuclear carboxylic acids, phenols, amines, and sulfonic acids adsorbed on paper, silica, alumina, and other substrates exhibit strong triplet phosphorescence at room temperature, with no evidence of quenching by oxygen. No phosphorescence has been observed with nonionic materials. The spectra are similar to those of frozen solutions at −196°C, and the technique provides a simple means of demonstrating phosphorescence phenomena, identifying unknown materials, and investigating the spectra of triplet states.*

With a few exceptions, strong phosphorescence (efficient triplet state emission) of organic molecules has been observed only in the gas phase, or in rigid media, usually at very low temperatures (*1*). Accordingly, we were surprised to observe that a variety of ionic organic molecules exhibit intense phosphorescence at room temperature when adsorbed on paper, silica, alumina, asbestos, glass fibers, and other supports. We have been unable to find any comparable observation in the literature (*2*), but essentially every salt of a carboxylic acid, phenol, amine, or sulfonic acid investigated which might be expected to show visible phosphorescence does so, but no emission was observed from any nonionic material examined nor from any nonadsorbed materials in the solid state (*3*). Identical results were obtained under O_2 or N_2, but only thoroughly dried samples phosphoresce, and phosphorescence disappears reversibly when samples are exposed to moist air.

Both excitation and emission spectra obtained with an Aminco-Keirs spectrophotophosphorimeter matched closely (except for slight line broadening) those obtained from frozen solutions at −196°C (Fig. 1). Table 1 is a

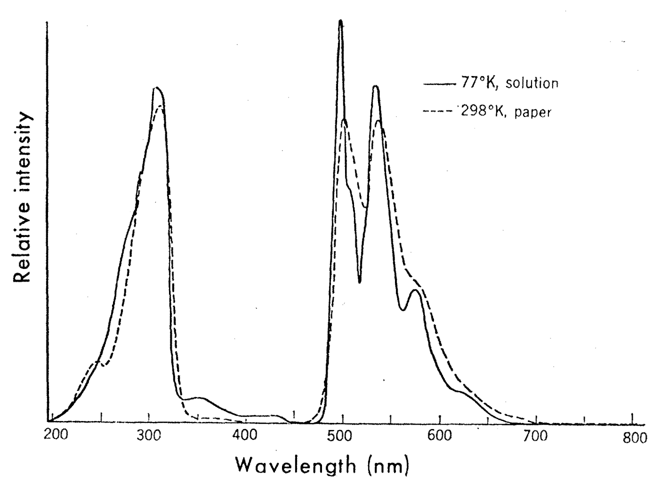

Fig. 1. Comparison of emission and excitation spectra for a frozen solution of 4 m*M* naphthalic acid in 1*M* sodium hydroxide at 77°K with those measured on dried paper at ambient temperature.