MAGNETIZATION OF CELESTIAL BODIES WITH SPECIAL APPLICATION TO THE PRIMEVAL EARTH AND MOON

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Abstract. The magnetic fields of celestial bodies are usually supposed to be due to a 'hydromagnetic dynamo'. This term refers to a number of rather speculative processes which are supposed to take place in the liquid core of a celestial body. In this paper we shall follow another approach which is more closely connected with hydromagnetic processes well-known from the laboratory, and hence basically less speculative. The paper should be regarded as part of a general program to connect cosmical phenomena with phenomena studied in the laboratory.

As has been demonstrated by laboratory experiments, a poloidal magnetic field may be increased by the transfer of energy from a toroidal magnetic field through kink instability of the current system. This mechanism can be applied to the fluid core of a celestial body. Any differential rotation will produce a toroidal field from an existing poloidal field, and the kink instability will feed toroidal energy back to the poloidal field, and hence amplify it.

In the Earth-Moon system the tidal braking of the Earth's mantle acts to produce a differential angular velocity between core and mantle. The braking will be transferred to the core by hydromagnetic forces which at the same time give rise to a strong magnetic field. The strength of the field will be determined by the rate of tidal braking.

It is suggested that the magnetization of lunar rocks from the period -4 to -3 Gyears derives from the Earth's magnetic field. As the interior of the Moon immediately after accretion probably was too cool to be melted, the Moon could not produce a magnetic field by hydromagnetic effects in its core.

The observed lunar magnetization could be produced by such an amplified Earth field even if the Moon never came closer than 10 or 20 Earth's radii.

This hypothesis might be checked by magnetic measurements on the Earth during the same period.

1. Hydromagnetic Mechanisms Generating a General Magnetic Field

The magnetic fields of celestial bodies are usually supposed to be due to a 'hydromagnetic dynamo'. This term refers to a number of speculative processes which are supposed to take place in the liquid core of a celestial body. Although some of these processes may be of importance in certain cases we shall here follow another approach which is more closely connected with hydromagnetic processes well-known from the laboratory and hence basically less speculative (Alfvén, 1961; Alfvén and Fälthammar, 1963, p. 122–129; Alfvén, 1972).

2. Model

We consider as a model for the Earth a sphere (radius R_E) with a liquid core (radius R_c) surrounded by a solid mantle. We assume that there are constant azimuthal

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currents I_c flowing symmetric to the axis in the core, producing a poloidal magnetic field which at the surface R_E is observed as a 'dipole field'. Both the core and the mantle rotate with the same angular velocity Ω_0, Figure 1.

We suppose next that there is a difference in angular velocity $\Delta\Omega = \Omega_c - \Omega_m$ between the core and the mantle. Then the core will act as a unipolar inductor with an electromotive force between the axis and the equator of the core: i.e.,

$$V = \int_0^{\pi/2} B_r R_c^2 \Delta\Omega \cos\phi \, d\phi, \tag{1}$$

where B_r is the radial magnetic field component, and ϕ the latitude angle (SI-units are used). If the conductivity is finite both in the core and the mantle this will cause meridional currents in the mantle which, in case of the Earth, flow towards the equatorial plane from both poles, Figure 2. The circuit will be closed by currents in the core. If the difference in angular velocity is produced suddenly, a set of hydromagnetic waves will be caused. When these have been damped (e.g., by finite conductivity) the current system may be idealized, without loss of the essential physical properties, as currents along the axis, in both hemispheres directed away from the center, and a radial inward current in the equatorial plane, Figure 2.

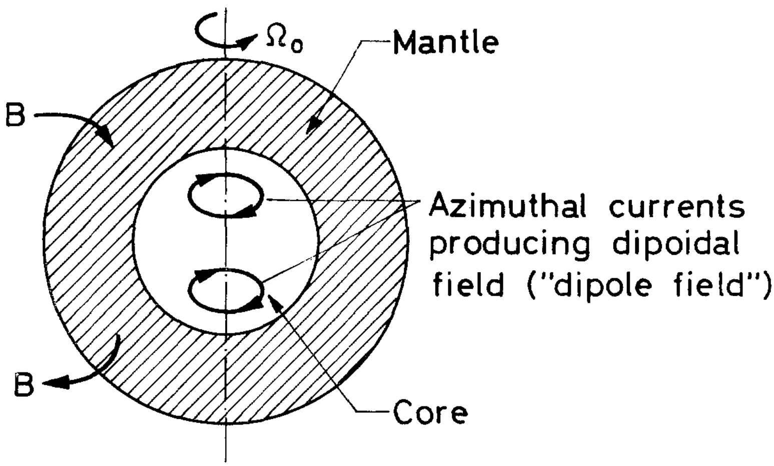


Fig. 1. Primary currents.

The magnetic field from this current system consists of two regions of toroidal magnetic field, one in the northern hemisphere where the field is directed eastward and the other in the southern hemisphere where it is westward. Superimposed on the original poloidal field it forms a 'twisted' magnetic field (which can be derived immediately by using the common 'frozen in' picture).

When deriving Equation (1) we assumed for simplicity the core and the mantle

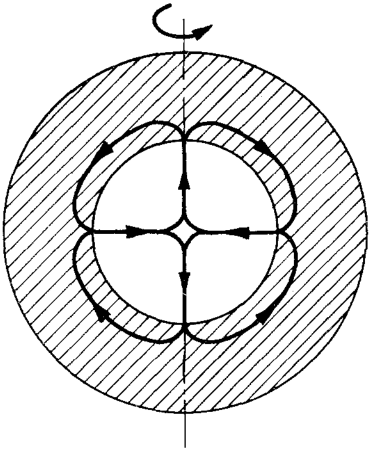


Fig. 2. Induced current system.

rotating as solid bodies. If instead the angular velocity is a function of the radius, the unipolar induction will still work and give an emf of the same order of magnitude.

3. Kink Instability

If the difference in rotational velocity persists, the unipolar induction will cause the toroidal magnetic field to increase until it reaches a value which is given by the emf, (Equation (1)) and the conductivity, Figure 3. In case the conductivity is sufficiently high, the toroidal magnetic energy will become comparable to the poloidal magnetic energy after some time. This may cause the axial currents to develop a kink instability.

This type of instability is a well-known phenomenon in laboratory physics, indeed it was one of the first obstacles to the early thermonuclear projects. It is illustrated by a plasma experiment by Lindberg *et al.* (1960) which aimed especially at the clarification of the problem how celestial bodies become magnetized. In next paragraph we shall give a brief review of the experiment.

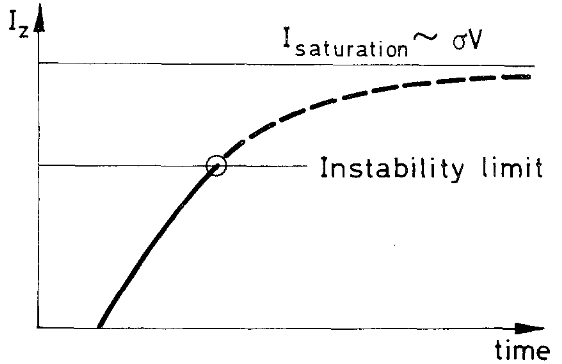


Fig. 3. The induced current may become unstable before reaching its saturation value.

The kink instability means that an initially rectilinear axial current twists into a helix. This implies that the current gets an azimuthal component. Experiments and theory show that *this current flows in the same direction as the original azimuthal current and hence amplifies the original poloidal magnetic field.*

Applying these results to the situation we are discussing, we expect the instability to occur in both the northern and the southern hemispheres, Figure 4. Hence we have found a very simple *field amplification mechanism.*

In our simple model the mechanism requires a difference in angular velocity between core and mantle. One way in which a differential velocity can arise is through tidal

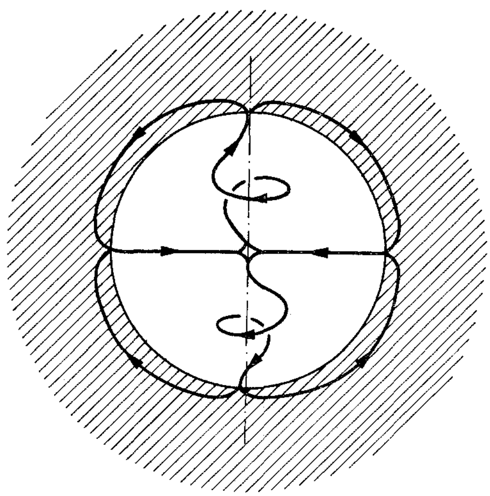


Fig. 4. Kink instabilities amplify primary current.

braking of the mantle. This seems to be of great importance in the Earth-Moon system as we will see in Section 8. An initial poloidal magnetic field is also required, but this may be very weak, and any stray field will suffice.

Thus, if in an original poloidal magnetic field there is a difference in rotational velocity, toroidal magnetic fields are produced which because of the kink instability feed energy into the original poloidal field. Kinetic energy from the differential rotation is transferred into increased poloidal (and toroidal) magnetic field energy.

The flux amplification mechanism is linear in that sense that it occurs when a certain ratio of B_ϕ/B_z is exceeded, independent of the absolute magnitude of the field strength. This implies that an initially very weak field can be amplified, but also that there is no inherent amplitude limitation. However, as the field becomes stronger, the magnetic coupling between core and mantle begins to play a role and tends to establish isorotation. The field will become limited when a large fraction of the kinetic energy delivered by the core is transferred into magnetic energy. (This is finally dissipated as heat due to resistive losses).

The strength of the field will consequently be determined *by the tidal braking.*

The mechanism we discuss can probably be generalized also to the case when the differential velocity is caused by other effects – e.g., thermal convection.

4. The Plasma Ring Experiment

The principle for formation of magnetized plasma rings by means of a coaxial plasma gun is illustrated in Figure 5a, b, c. The ring is produced by a high current electric discharge in hydrogen between coaxial electrodes A and C, Figure 5a. The

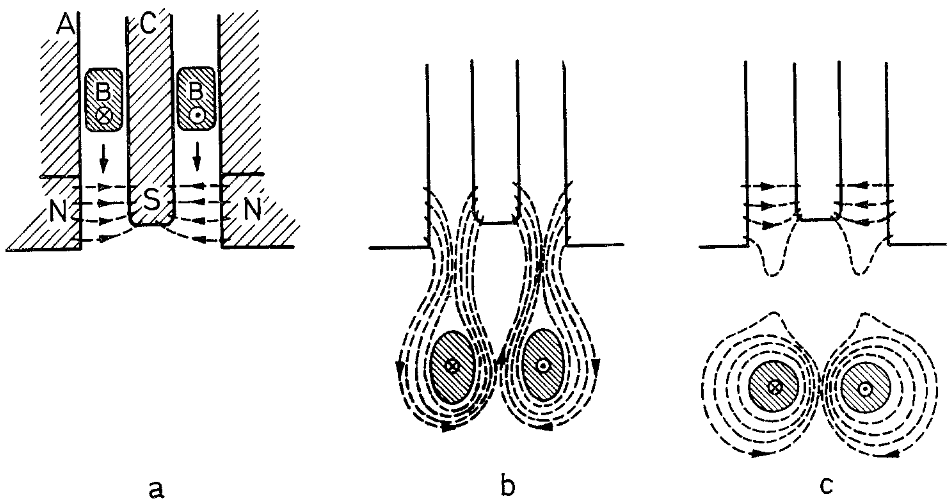


Fig. 5. Formation of a magnetized plasma ring.

gas becomes almost fully ionized, and due to the azimuthal magnetic field B, which is set up by the discharge current above and within the plasma, a magnetic pressure ($\bar{j} \times \bar{B}$-force) develops, which accelerates the plasma ring downwards, towards the muzzle of the gun.

At the muzzle a radial magnetic field is applied. When a plasma enters this field azimuthal currents are induced in it so that the lines of force will be stretched out, Figure 5b. Finally, they can be expected to 'break', so that a free plasma ring with a poloidal magnetic field is formed, Figure 5c. Provided the conductivity of the plasma is high the magnetic flux through the ring is expected to be conserved and equal to the flux initially present in the center electrode of the gun (or somewhat weaker, because of resistive losses).

In order to test this experimentally a device according to Figure 6 was used. The current to the gun is supplied from a condenser bank, C, through a spark gap switch, G. The outer electrode is of stainless steel, the center electrode of soft iron, forming part of a magnetic circuit, M, magnetized by dc before the experiment. The gun is open into a drift tube of glass and the whole volume is initially filled with hydrogen, typically at 0.1–0.5 Torr. Around the glass tube single turn wire loops, L, are mounted

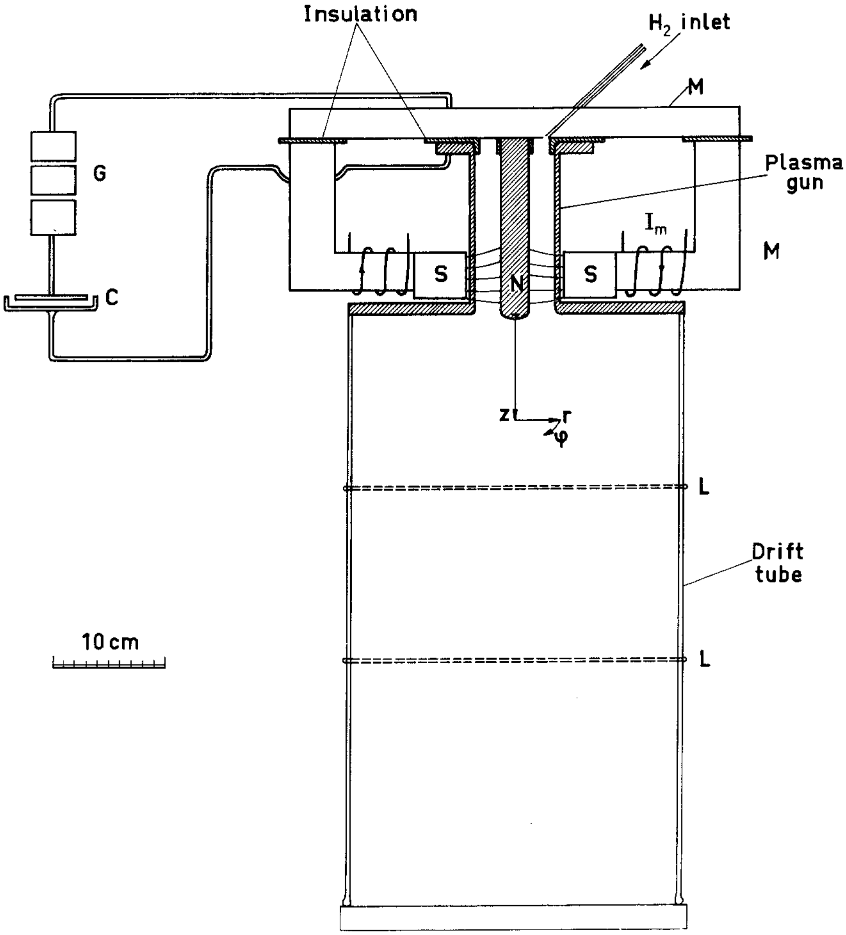


Fig. 6. The plasma gun with drift tube and loops for magnetic flux measurements.

for magnetic flux measurements. Magnetic probe coils introduced in glass tubes through the bottom plate were used for local measurements, and the plasma was also studied by high speed photography.

5. Experimental Evidence of Magnetic Flux Amplification

Experiments showed that magnetized plasma rings could be formed, that their lifetime was long compared to the duration of the current in the gun and that the magnetic flux trapped through the hole under certain conditions could be *several times stronger than expected* (Lindberg *et al.*, 1960; Lindberg and Jacobsen, 1961, 1964).

Typical oscillograms when flux amplification occurs are shown in Figure 7. The upper curve shows the discharge current in the gun which has a rapidly damped, oscillatory character. The lower curves show the flux measured by the two loops. The

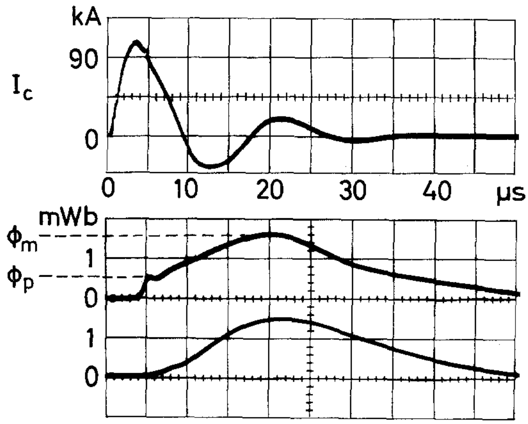
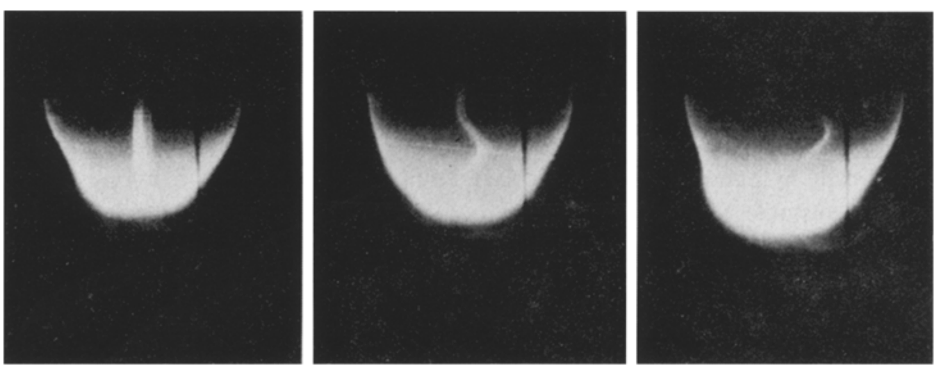


Fig. 7. Oscillograms showing discharge current and magnetic flux measured by two loops at 15 and 30 cm distance from the gun. Static applied flux $\phi_s = 0.55$ mWb.

initially applied static magnetic flux in the center electrode was $\phi_s = 0.55$ mWb. It is seen that the measured flux rises slowly to a maximum, ϕ_m, in this case equal to three times Φ_s. On the upper loop there is a plateau, Φ_p, approximately equal to Φ_s.

The mechanism of the flux amplification was clarified by taking pictures of the plasma just outside the muzzle of the gun, Figure 8a–c. The boundary between plasma and neutral gas is strongly luminous, the plasma above it is darker. The current from the center electrode continues at first straight on in the elongation of the center electrode and is visible as the straight luminous central column in Figure 8a. (The luminosity is due to the presence of neutral gas in the elongation of the center electrode.) A fraction of a microsecond later the central current column becomes unstable and turns into a helix, which rapidly expands, Figure 8b and c. The helical current path sets up an additional poloidal magnetic field, which at first is *closed*



(a) (b) (c)

Fig. 8. Central column of plasma turning into a helix. Pictures taken between 4.0 and 4.6 μs after ignition.

inside the plasma and therefore cannot be measured with the external loops. The poloidal flux trapped from the gun on the contrary is *closed outside* the plasma, and is therefore immediately measured by the loops, when the plasma expands towards the glass tube (ϕ_p). Later, when the plasma ring cools off, the internal flux, originating from the helical instability, diffuses out through the glass wall and is measured by the loop (ϕ_m).

In order to decide whether the helical current path is left-handed or right-handed two methods were used, by photography from two directions (using a mirror), and by means of magnetic probes. In all experiments the current in the gun was directed from the outer to the center electrode, but the magnetic field at the muzzle could be applied in either direction. It was found that when the field was directed radially outwards, the helix became left-handed, and when it was inwards the helix became right-handed. *This means that the helical instability always develops with such a sense that the poloidal magnetic flux becomes amplified. The flux amplification phenomenon occurs independently of whether the initial axial current and magnetic field are parallel or antiparallel.*

There never occurred a flux decrease, but there were experiments when no flux amplification occurred. This happened when the voltage and current were increased above a certain limit; then a secondary break-down took place across the insulator in the top of the gun so that only part of the current passed out of the gun. This current was obviously too low to become unstable. This could also be seen from the luminous central column in the plasma, which in those experiments remained straight all the time.

One difficulty is to understand how the turns of the helix can collaps to a single turn of azimuthal current detached from the gun. For this process the occurrence of regions of zero magnetic field between adjacent turns is likely to play a great role for the annihilation of the oppositely directed radial magnetic fields between turns. An extremely fast flux transfer rate at an X-type neutral point has recently been observed experimentally by Bratenahl and Yeates (1970). Unfortunately the theoretical treatment of their result is not of the same quality as their experiment.

6. The Condition for Instability

The stability of twisted cylindrical magnetic fields in a conducting liquid was studied theoretically by Lundquist (1951). He found that the magnetic field in a long cylinder becomes unstable when the average energy density of the azimuthal magnetic field component exceeds double the average energy density of the axial magnetic field: i.e.,

$$\langle B_\phi^2 \rangle > 2 \langle B_z^2 \rangle . \tag{2}$$

Transferring this result to our field geometry we can conclude that the condition for instability could be approached either through an increase of the toroidal field or through a decrease of the poloidal field or a combination of both types of variation. As concerns the plasma ring experiment it is the increase of the azimuthal field (due to the increasing axial current) that leads to instability. In the Earth's interior it may be the decay of the poloidal magnetic field that leads to instability. This seems likely since there is no energy supply to the poloidal field (except through the flux amplification mechanism), while the toroidal field has a continuous energy supply due to the unipolar induction. Going more into detail we should have also to take into account spatial movement of the current system. This makes the situation still more complicated.

If on the other hand we consider a hypothetic stationary state, we will find that it must be unstable under certain conditions. If we assume a constant poloidal field, and a constant difference in angular velocity, we will, according to Equation (1) get a constant emf, and this would give rise to and maintain a system of axial currents. These will grow until a quasi-stationary state is reached in which the strength of these currents is proportional to the emf and the conductivity. However, if before this state is reached the axial currents exceed a certain strength (in relation to the original poloidal magnetic field) instability would occur, Figure 3. Thus we can state: *Provided the differential angular velocity and the conductivity exceed certain critical values, the axial current system must necessarily become unstable and lead to amplification of the original poloidal magnetic field.*

A difference in angular velocity between the core and the mantle is always maintained due to the tidal braking of the mantle. As concerns the strength of the original poloidal field there is no lower limit. If the differential velocity and the conductivity are sufficient, amplification of the poloidal field will occur.

7. Critical Differential Angular Velocity

In order to make an order of magnitude estimate of the current in the axial current system we approximate the conductance as that of a cylinder with both diameter and length equal to the radius R_c of the core. We find the current in the cylinder

$$I_z \simeq \frac{\pi}{4} \sigma R_c V , \tag{3}$$

where V is the emf, Equation (1), which we may approximate by

$$V \simeq \tfrac{1}{2} B_z R_c^2 \, \Delta\Omega . \tag{4}$$

The azimuthal magnetic field due to I_z at e.g. $R_c/2$ becomes

$$B_\phi = \frac{\mu_0 I_z}{\pi R_c} . \tag{5}$$

Combining Equations (3) to (5) we get

$$\frac{B_\phi}{B_z} = \tfrac{1}{8} \mu_0 \sigma R_c^2 \, \Delta\Omega . \tag{6}$$

Introducing this into Lundquist's criterion (2), we find the approximate lower limit for $\Delta\Omega$ necessary for instability to occur

$$\Delta\Omega > \frac{8\sqrt{2}}{\mu_0 \sigma R_c^2}. \tag{7}$$

We recognize that

$$\tau = \mu_0 \sigma R_c^2 \tag{8}$$

is the time constant for the decay of the magnetic field in a sphere of radius R_c. If we assume $\sigma = 10^5$ to 10^3 AV^{-1}m^{-1}, i.e. 10^{-3} to 10^{-5} times the conductivity of copper, and $R_c = 3 \times 10^6$ m, we find $\tau = 10^{12}$ to 10^{10} s. For simplicity we have assumed the same value of σ for the core and the mantle. However, it is believed that the conductivity of the mantle is two or three orders of magnitude lower than that of the core. On the other hand the outermost layers of the core are likely to corotate with the mantle and the meridional currents may flow mainly in that layer of the core.

Returning to our simple model we find the lower limits $\Delta\Omega = 10^{-11}$ to 10^{-9} s, i.e. one turn per 2×10^4 to $2 \cdot 10^2$ yr resp. A differential angular velocity between core and mantle of this magnitude has to be reached as a consequence of tidal braking of the mantle, in spite of the fact that viscosity (and electromagnetic coupling) tend to establish isorotation. As we neither know the chemical composition of the interior of the Earth nor the conductivity and viscosity of a certain material at the pressures and temperatures in the core, there is no possibility to judge whether the required differential velocity can be reached or not.

Independent of this, tidal braking of the mantle should make its angular velocity lower than that of the core, and magnetic anomalies, if connected to the core, should show an eastward drift. This is obviously in contradiction with the westward drift observed during the last centuries. According to Hide (1967) and Yukutake (1972) the westward drift may be temporary and is likely to be an effect of oscillations or convection in the core.

The special model we have discussed refers to an effect primarily caused by tidal braking of the spin of the mantle. This type of braking is applicable only to planets having satellites large enough to produce a sufficient tidal braking (which means only to the Earth and Neptune) (Alfvén and Arrhenius, 1970a, Chapter 5). However, when a central body produces a set of secondary bodies around it, this requires a transfer of angular momentum from the spin of the central body to orbital momentum of the secondary bodies. The transfer is affected by a set of currents flowing between the surface (or ionosphere) of the central body and the surrounding plasma cloud. In this way the mantle of the central body is braked in about the same way as by tidal action. Hence our mechanism for flux amplification may be applicable also to e.g. planets generating a group of satellites around them.

8. Coupling Between Lunar Motion and Magnetic Field

Lunar records indicate that the Moon was immersed in a magnetic field of the order

$2 \cdot 10^{-2}$ G during the period -4 to -3.2 Gyr (see e.g. Strangway *et al.*, 1973; Gose *et al.*, 1973). As it is likely that the primeval Moon did not have a liquid core (Alfvén and Arrhenius, 1970b, Chapter 9) and hence could not produce a magnetic field of its own, it is suggested that the magnetic field derived from the Earth. This requires either that the Moon was very close to the Earth during a long period or that Earth's magnetic field was much stronger than the present field or both.

Assuming that the differential angular velocity between mantle and core exceeds the critical value, we will now derive quantitative relations between the rate of tidal braking of the Earth and the strength of the magnetic field at the Earth's surface and on the Moon.

The rotational energy of the core is

$$W_{\text{rot}} = \frac{1}{2} \cdot \frac{4\pi}{3} \alpha R_c^5 \theta \Omega_c^2 , \tag{9}$$

where θ is the average density of the core, and α a factor, which for a homogeneous sphere is $\frac{2}{5}$, but somewhat smaller if there is a mass concentration towards the center.

The rate of kinetic energy loss is

$$\frac{\mathrm{d}W_{\text{rot}}}{\mathrm{d}t} = \frac{4\pi}{3} \alpha R_c^5 \theta \Omega_c \frac{\mathrm{d}\Omega_c}{\mathrm{d}t} . \tag{10}$$

The main braking of the Earth's spin is due to the tidal effects produced at the capture of the Moon and during its subsequent orbital revolution. These processes have reduced the spin period of the primeval Earth (which may have had a period of 5 h) to the present value. As a first approximation we assume an exponential slowing down of the angular velocity during $3 \cdot 10^9$ yr. This corresponds to a time constant $T \simeq 2 \cdot 10^9$ yr, and we find that

$$\frac{\mathrm{d}\Omega_c}{\mathrm{d}t} = - \frac{\Omega_c}{T} , \tag{11}$$

equal to $-6 \cdot 10^{-21}$ s^{-2}. Taking into account that the Moon has been much closer to the Earth during a certain interval (Alfvén, 1962; Alfvén and Arrhenius, 1969, 1972) $\mathrm{d}\Omega_c/\mathrm{d}t$ may have been one or two orders of magnitude larger. If the Moon e.g. has been at a distance of 20 R_E, i.e. one third of the present distance, the tidal braking should have been roughly 3^3 times the present value and we could assume $\mathrm{d}\Omega_c/\mathrm{d}t \simeq -10^{-19}$ s^{-2}.

If no energy were supplied to the magnetic field it would decay due to resistive losses with a time constant

$$\tau = \mu_0 \sigma R_c^2 \tag{8}$$

as previously mentioned in Section 7. Thus the rate of energy dissipation due to resistive losses is related to the total magnetic energy by

$$\frac{\mathrm{d}W_{\text{mag}}}{\mathrm{d}t} = - \frac{W_{\text{mag}}}{\tau/2} . \tag{12}$$

We assume that a fraction, γ, of the kinetic energy loss of the core is transferred to magnetic energy to cover these losses – such that

$$\gamma \frac{\mathrm{d}W_{\mathrm{rot}}}{\mathrm{d}t} = -\frac{W_{\mathrm{mag}}}{\tau/2}. \tag{13}$$

The magnetic energy is

$$W_{\mathrm{mag}} = \beta \frac{B_c^2}{2\mu_0} \frac{4\pi}{3} R_c^3, \tag{14}$$

where B_c is the equatorial magnetic field of the core, and β is a constant, which is equal to two if the magnetization of the core is homogeneous, but larger if, as expected, the field is stronger in the central parts.

Combining Equations (8)–(14) we find that

$$B_c = \mu_0 R_c^2 \left(-\frac{\alpha\gamma}{\beta} \sigma\theta\Omega_c \frac{\mathrm{d}\Omega_c}{\mathrm{d}t} \right)^{1/2}. \tag{15}$$

If the Moon is situated in the equatorial plane of the Earth at a distance $R_{\mathrm{M}} = \varrho_{\mathrm{M}} R_{\mathrm{E}}$, where R_{E} is the radius of the Earth, and we assume the Earth's field to have dipole character outside the core, the Moon will be immersed in a magnetic field

$$B_{\mathrm{M}} = B_c \left(\frac{R_c}{\varrho_{\mathrm{M}} R_{\mathrm{E}}} \right)^3. \tag{16}$$

9. Numerical Estimate of the Magnetic Field of the Primeval Earth and Moon

We introduce the following numerical values into Equations (15) and (16):

$$\begin{aligned}
\alpha &= 0.3, \\
\beta &= 3, \\
\gamma &= 0.25, \\
R_c &= 3 \times 10^6\ \mathrm{m}, \\
R_{\mathrm{E}} &= 6 \times 10^6\ \mathrm{m}, \\
\theta &= 8 \times 10^3\ \mathrm{kg\ m^{-3}}, \\
\Omega_c &= 3 \times 10^{-4}\ \mathrm{s^{-1}}\ \text{(corresponding to a spin period of 5 h)}, \\
\frac{\mathrm{d}\Omega_c}{\mathrm{d}t} &= -10^{-19}\ \mathrm{s^{-2}}, \\
\sigma &= 10^4\ \mathrm{AV^{-1}\ m^{-1}}\ \text{(corresponding to } \tau = 10^{11}\ \mathrm{s} = 3 \times 10^3\ \text{yr)}, \\
\varrho_{\mathrm{M}} &= 20.
\end{aligned}$$

Then we find that

$$\begin{aligned}
B_c &= 0.1\ \mathrm{Vs\ m^{-2}}\ (1000\ \mathrm{G}), \\
B_{\mathrm{M}} &= 1.6 \times 10^{-6}\ \mathrm{Vs\ m^{-2}}\ (0.016\ \mathrm{G});
\end{aligned}$$

ϱ_M being the parameter with greatest influence on B_M since both $d\Omega_c/dt$ and B_M/B_c are proportional to ϱ_M^{-3} so that the value of B_M becomes proportional to ϱ_M^{-6}. We think our choice of $\varrho_M = 20$ is conservative.

The strength of the Earth's magnetic field on the Moon which we have calculated, $B_M = 0.016$ G, is quite sufficient to magnetize material on the Moon provided it is heated above its Curie point and cooled in the field (Strangway *et al.*, 1973, Gose *et al.*, 1973). The necessary heating could be local due to meteorite impacts.

The age of the lunar samples ranges between 3.2 and 4 Gyr and it is necessary that the Moon was immersed in a magnetic field during that time. This could be possible if the Moon was trapped in a resonance orbit at 10 to 20 Earth radii as previously suggested by Alfvén and Arrhenius (1969, 1972).

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References

Alfvén, H.: 1961, *Astrophys. J.* **133**, 1049.
Alfvén, H.: 1963, *Icarus* **1**, 357.
Alfvén, H.: 1972, in K. Schindler (ed.), *Cosmic Plasma Physics*, Plenum Press, N.Y.-London.
Alfvén, H. and Arrhenius, G.: 1969, *Science* **165**, 11.
Alfvén, H. and Arrhenius, G.: 1970a, *Astrophys. Space Sci.* **8**, 338.
Alfvén, H. and Arrhenius, G.: 1970b, *Astrophys. Space Sci.* **9**, 3.
Alfvén, H. and Arrhenius, G.: 1972, *The Moon* **5**, 210.
Alfvén, H. and Arrhenius, G.: 1973, *Astrophys. Space Sci.* **21**, 117.
Alfvén, H. and Fälthammar, C.-G.: 1963, *Cosmical Electrodynamics*, Oxford, p. 120–129.
Bratenahl, A. and Yeates, C. M.: 1970, *Phys. Fluids* **13**, 2696.
Gose, W. A., Strangway, D. W., and Pearce, G. W.: 1973, *The Moon* **7**, 196.
Hide, R.: 1967, *Science* **157**, 55.
Lindberg, L. and Jacobsen, C. T.: 1961, *Astrophys. J.* **133**, 1043.
Lindberg, L. and Jacobsen, C. T.: 1964, *Phys. Fluids. Suppl.* **7**, S44.
Lindberg, L., Witalis, E., and Jacobsen, C. T.: 1960, *Nature* **185**, 452.
Lundquist, S.: 1951, *Phys. Rev.* **83**, 307.
Strangway, D. W. *et al.*: 1973, 'Proc. 18th Annual Conf. on Magnetism and Magnetic Materials', *J. Appl. Phys.*, in press.
Yukutake, T.: 1972, *J. Geomag. Geoelect.* **24**, 19.