On the Mechanism of the Magnetic Dynamo of the Planets

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Results of testing the effectiveness of the theory of precessional dynamos in the generation of the magnetic fields of the planets are presented. It is shown that the magnetic state of Earth and of the planets Mars, Jupiter, and Venus can be satisfactorily described by the formula

$$H_i = H_3 \frac{V_i}{V_3} \frac{T_3}{T_i} \frac{\Omega_i}{\Omega_3} \frac{\sin\alpha_1}{\sin\alpha_3}$$

where *H*, *v*, *T*, Ω, and α are the dipole fields, volumes of liquid cores, periods of rotation, rates of precession, and angles between precession vector and angular rotation, respectively, for the planets and Earth. The v_i corresponds to known models of the internal structure. It is shown that the magnetic state of Mercury satisfies this formula if the dynamic flattening of the planet $f = 5.7 \times 10^{-5} - 8.3 \times 10^{-5}$.

The idea that the magnetic field of the Earth is related to the operation of some sort of dynamo mechanism in its highly conductive liquid core has now been largely confirmed.

Modern kinematic models of the terrestrial magnetic dynamo have been found capable of describing the basic peculiarities of the terrestrial magnetic field (refs. 1 and 2). At the same time, no physical theory of the terrestrial field as yet presented considers the actual parameters and processes in the core of the Earth. This is particularly true concerning the uncertainty of the mechanism generating the terrestrial dynamo. Three mechanisms are known:

1. Convection in the core under the influence of thermal sources (refs. 3 and 4).
2. Convection under the influences of forces of gravity (ref. 5).
3. Convection in the core caused by precession of the axis of rotation of the Earth (refs. 6 and 7).

With a model of a purely iron-nickel core, the radioactive elements U and Th are forced out because of their chemical and physical incompatibility with iron at the pressures present in the core. Thermal sources in the core have been related to processes of continuing differentiation of matter in the Earth: the settling of heated iron, melted from the mantle (ref. 3) and the latent heat of melting, liberated upon crystallization of the outer core at the boundary with the inner solid core (ref. 4).

In order for thermal convection to occur in the liquid core of the Earth, the temperature gradient must exceed the adiabatic gradient. In a number of publications during 1971–1973 (ref. 8), concepts of the isothermal state of the core were discussed. A stable thermal state is incompatible with thermal convection in the core, to which the generation of the magnetic field is related. Ideas of the thermal conditions of the Earth's core have changed, on the basis of assumptions of the presence of radioactive potassium K^{40} in the core (ref. 9).

The effectiveness of thermal sources in any mechanism of generation of the magnetic field has been assumed to be low, because of the low efficiency of thermal machines. According to one hypothesis (ref. 5), the processes of differentiation of material indicated by Urey and Verhoogen are actually involved in the generation of the magnetic field, but only because of the gravitational energy released during these processes. Convection in the core is caused by direct upwelling of impurities of light silicon, accompanying the process of crystallization and sinking of heavy iron.

The hypothesis of the gravitational nature of the "motor" driving the Earth's dynamo encounters great difficulties in light of current hypotheses of the nonhomogeneous formation of the planets (refs. 10 and 11). As concerns thermal sources, their role is at least as great in the creation of the necessary conductivity and viscosity in the core.

Malkus suggested that the precession of the Earth was the motive force of the magnetic dynamo. The precession of the planets is caused by the action of the gravitational fields of the Sun and other celestial bodies on the equatorial bulge of the rotating planets. The presence of precession, at an angular velocity Ω, results in an additional angular acceleration $\Omega = [\Omega \times \omega]$ and an additional inertial force $F_\eta = -\rho[\overline{\Omega} \times \overline{\omega}] \times \overline{r}$. Malkus called this the Poincaré force, after the man who first solved analytically the problem of the motion of a fluid in a precessing spheroidal container. The experiments performed by Malkus showed that with certain relationships of $\overline{\omega}$ and $\overline{\Omega}$ in the precessing liquid, turbulent flow arises, which is not predicted by classical theory.

The rate of precession of the planet is directly proportional to its dynamic flattening, and independent of its radius and mass. Since the core and mantle of the Earth have somewhat differing dynamic flattening, the gravity fields of the Sun and the Moon create different torques on the core and mantle, causing stress both in the core and in the mantle, which tend to equalize the rates of the two precessions. These stresses act on the liquid in the core, leading to the motion necessary for the operation of the dynamo. In the final analysis, the energy of the magnetic dynamo is taken from the kinetic energy in the Earth's rotation.

The details of the precessional mechanism generating the magnetic field have not been worked out. There are contradictory opinions concerning its effectiveness. Braginskiy (ref. 12) turned his attention to the fact that the speed of the liquid under the influence of the Poincaré force fluctuates with the frequency of the main rotation ω and therefore cannot directly influence slow processes in the dynamo. On the other hand Dolginov (ref. 13) notes that the precession of a liquid in a nonspherical envelope results in the appearance of flows of a spiral nature that are similar to tidal flows. Flows of a spiral nature facilitate the generation of magnetic fields (ref. 14).

At the present time, the magnetic fields of the Earth, Venus, Mars, Jupiter, and Mercury have been studied. For the first four planets, certain models of the internal structure are known (refs. 15–20), as well as the parameters of rotation and dynamic flattening (refs. 21 and 22), and magnetic fields (refs. 23–27).

This paper presents a model and results of a test of the effectiveness of the mechanism of the precessional dynamo in the generation of the magnetic fields of the Earth, Mars, and Jupiter. Furthermore, conditions are studied under which the magnetic states of Venus and Mercury can be explained, on the basis of the hypothesis of precession as the motive force of the planetary dynamo.

The approach is based on the following assumptions:

1. The processes of generation of the field in the planets are similar in terms of modeling and are determined by a number of dimensionless parameters.
2. The magnetic fields are proportional to the volumes of the liquid cores of the planets (ref. 28).
3. The rates of convection of matter are proportional to the Poincaré force F_η

$\sim [\bar{\omega} \times \bar{\Omega}] \times \bar{r}$, where ω is the angular velocity of rotation, and Ω is the angular velocity of precession.

4. Under these conditions, a simple dependence between the dipole fields of two planets 1 and 2 is assumed to exist:

$$\gamma_{1\text{-}2} \sim \frac{V_1}{V_2} \cdot \frac{T_2}{T_1} \cdot \frac{\Omega_1}{\Omega_2} \cdot \frac{\sin \alpha_1}{\sin \alpha_2}, \quad (1)$$

where γ is the ratio of the dipole fields $\frac{H_{01}}{H_{02}}$ on the surface at the magnetic equator; α is the angle between vectors ω and Ω; V is the volume of the liquid core, and T the rotation period. Volume V_1 is the liquid core of the Earth, and is assumed known (ref. 19).

Earth, Mars, Jupiter

We present below the values of the parameters T, Ω, α, and H_0 of three rapidly rotating planets.

Formula (1) has one unknown, V_2, the volume of the liquid core of the second planet. The dimensions of the core of Mars have been very approximately determined. The measured values of radius, mass, and moment of inertia are satisfied in various models with significantly differing core dimensions R_c. In the model of Kozlovskaya (ref. 15), $R_c = 960$ km; in the model of Ringwood (ref. 16), $R_{c_{\text{ext}}} = 1720$ km and $R_{c_{\text{int}}} = 1510$ km; in the model of Binder and Davis (ref. 17), $R_c = 1250$ km; in the model of Anderson (ref. 18), $R_c = 1350$ km; and in the model of Johnston and Toksöz (ref. 19), $R_c = 1300$ km. The ratios of volumes of the cores of the Earth and Mars which they obtain are 45, 26, 20, 16, and 18, respectively.

The dimensions of the magnetically active area of Jupiter are determined primarily by the depth at which hydrogen is converted to the metallic state. According to Zharkov et al. (ref. 19), this occurs at depths of $r/R_J = 0.8$. The magnetically active area apparently begins at a point ranging from $r/R_J = 0.7$ to $r/R_J = 0.15$. The volume of the magnetically active area of Jupiter, with these dimensions, exceeds the volume of the liquid core of the Earth by some 1600 times. Now, formula (1) and the data of table 1 lead to the following values of calculated and measured field strength ratios between the Earth and Mars ($\gamma_{e\text{-}m}$ using the various models), Jupiter and Earth ($\gamma_{j\text{-}e}$); $\gamma_{e\text{-}m} =$ 315, 180, 140, 110, and 130, respectively, while measured $\gamma_{e\text{-}m} = 470$. Calculated $\gamma_{j\text{-}e} = 22$, while measured $\gamma_{j\text{-}e} = 13$.

We note the moderately good degree to which the measured and calculated values of dipole field ratios of the three rapidly rotating planets agree with this tremendous difference in volumes and fields.

Venus

The planet Venus apparently does not have a magnetic field of its own which exceeds 10 gammas (refs. 24 and 27). It is natural to expect that formula (1) will take note of this fact with some accuracy. According to the data from the trajectory measurements on Mariner 5 and radar studies of the planet, the radius of Venus $R_V = 6052.5 \pm 2.5$ km (ref. 29).

The period of rotation, as determined by Dyce et al. (ref. 30), is 245.1 ± 0.7 days; according to the data of Carpenter (ref. 31), it is $\sim 243 \pm 1$ days.

The inclination of the axis of rotation relative to the pole of the orbit, according to Dyce et al. (ref. 30), is $\sim 3.3 \pm 0.4°$; according to Carpenter (ref. 31), $\sim 2.2°$. Trajectory measurements of Mariner 5 (ref. 32)

Table 1.—*Parameters of Rapidly Rotating Planets*

	T	Ω	α	H_0, gammas
Earth	23h 56m 04s	50.25 ″/yr	23.5°	30 000
Mars	24h 37m 23s	7.40 ″/yr	23.2°	64
Jupiter	9h 50m 56s	2.34 ″/yr	3°	400 000

have been used to estimate the degree of dynamic flattening $f = 1/100$ of this terrestrial planet. This value has been confirmed by the data from Mariner 10 ($f = 1/30\,000$). The precession of Venus results from the influence of the dipole gravitational field of the Sun. The rate of presession of Venus, with $f = 1/30\,000$, is $\Omega_v = 122''/\text{yr}$. We can further assume that the volume of the liquid core of Venus is equal to or only slightly less than the volume of the liquid core of Earth (ref. 20). Then formula (1) gives us, with $\alpha = 2.2°$ and $3.3°$, a field intensity $H_0 \leq 20$–30 gammas in comparison with the terrestrial magnetic field.

Thus, proceeding from formula (1), there is no need to postulate any difference in the internal structure of Venus from that of Earth, except on the basis of the fact that it has no significant magnetic field (refs. 33 and 34).

Mercury

For Mercury, data on most of the parameters included in formula (1) are quite indefinite. Nevertheless, there is reason to use (1) to estimate the limits of dynamic flattening of the planet Mercury. The flight of Mariner 10 produced new experimental data on the parameters of rotation and, we can hope, in the near future it will be possible to compare results and take into consideration the new experimental results.

For the value of the dipole magnetic field, assuming that it is intrinsic to the planet (ref. 26), there are at present two values available: 227 gammas and 380 gammas. The first of these values corresponds to the theoretical dipole, somewhat inclined to the axis of rotation and displaced from the center by 0.47 km, to achieve best agreement with the experimental data. The second value is produced from the data of the gasdynamic model of solar wind flow around the planet. The shock front was intersected in this experiment at an angle of $\sim 110°$ with respect to the direction to the Sun.

It is now generally accepted that Mercury rotates with a period of 58 days. For the angle of inclination of the axis of rotation to the plane of the orbit, widely different values have been given. According to radar data (ref. 30), an angle of $\alpha \simeq 28°$ is given. According to terrestrial photographs of Mercury (ref. 35), the axis of rotation is perpendicular to the plane of the orbit with an accuracy of $\sim 3°$. It is assumed (ref. 26) that the axis of the dipole makes an angle of $80 \pm 10°$ with the plane of the ecliptic. The orbital plane of Mercury makes an angle of $\sim 7°$ with the plane of the ecliptic.

Studies of the internal structure of Mercury, based on determinations of mass and radius, lead to comparatively large dimensions for the core of Mercury. Plageman (ref. 36) indicates $R_c = 2112$ km, and Kozlovskaya (ref. 37) indicates $R_c = 1730$ km.

With the existing uncertainties of most parameters, there is reason to take certain arbitrary parameters and estimate from them, the order of magnitude of a quite unknown quantity, the dynamic flattening. Let us take $H_0 = 250$ gammas, $R_c = 1800$ km, $\alpha = 20°$. Then, comparing with the Earth, from formula (1) we can estimate the rate of precession of Mercury: $\Omega_{\text{Merc}} = 190''/\text{yr}$. The dynamic flattening of Mercury f_{Merc} can be estimated by comparing the rate of precession of Mars and Mercury, since both planets precess under the influence of the gravitational field of the Sun.

$$f_{\text{Merc}} = \frac{R^3 ♂}{R^3_{\text{Merc}}} \cdot \frac{T ♂}{T_{\text{Merc}}} \cdot \frac{\Omega_{\text{Merc}}}{\Omega ♂} \cdot f ♂$$

Then where

$H_0 = 250$ gammas, $f_{\text{Merc}} = 5.7 \cdot 10^{-5}$

$H_0 = 380$ gammas, $f_{\text{Merc}} = 8.3 \cdot 10^{-5}$

These values are somewhat greater than those for the dynamic flattening of Venus.

Thus, even with the current uncertainty for a number of parameters of Mercury, formula (1) indicates that the fact of the existence of a magnetic field of Mercury (ref. 26) is not too surprising.

Correspondence of the Dynamo Model

1. In the theory of the terrestrial dynamo, the inclination of the axis of the dipole is not

considered to be a chance phenomenon, but rather a fact directly related to the mechanism of generation of the field (ref. 12).

Paleomagnetologists, on the other hand, consider the current orientation of the magnetic dipole to be a brief (in the geological scale) deviation from the position of symmetry (ref. 38).

The magnetic dipoles of Jupiter, Mars, and—apparently—Mercury, are inclined in relation to their axes of rotation. Furthermore, for Jupiter, as for Earth, the dipole is eccentric. The eccentricity of the dipole appears to be particularly great for Mercury.

2. Mercury, Earth, Mars, and Jupiter have direct rotation. However, the polarity of the magnetic fields of Mars and Jupiter is the reverse of the polarity of the current fields of Earth and Mercury. In kinematic models of the terrestrial dynamo, the sign of the field is not directly related to the direction of rotation, and the possibility of field reversals is explained by the action of instabilities in the mechanism of generation. The possible relationship of terrestrial field reversals with precession of its axis has been indicated by (ref. 39).

Experiments in the third decade of the space age should clarify the degree of regularity of the connections revealed between the planets' parameters of rotation, their structure, and their magnetic fields.

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