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On Magnetic Field Generation Mechanisms in Astrophysics

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Abstract. Magnetic chemically peculiar stars (CP stars) are characterized by a strong magnetic field, peculiar chemical composition and slow rotation. Since the origin and evolution of CP stars may be responsible for such unusual features, understanding the mechanisms of generation of the magnetic field is one of the ways to learn more about the CP star characteristics. At present there are two mechanisms of magnetic field generation considered in astrophysics, a fossil field hypothesis and turbulent dynamo theory. However, there is another mechanism of magnetic field generation. All the elementary particles including the most abundant, i. e. the protons, electrons, neutrons, have their own angular momenta and the corresponding magnetic momenta. Microscopic magnetic fields are determined generally by these magnetic momenta. Provided that microscopic magnetic fields are aligned, large–scale magnetic fields may be generated, which has been proved in the experiments of Barnett, Einstein and de Haas. This phenomenon is best illustrated by the experiments with iron. Analysis performed in the current study showed that all the large bodies of the Solar System have both an iron-nickel core and a magnetic field, which is proportional to the planet's core volume and its rotational velocity. We hypothesize that the reason for this phenomenon is a magnetic interaction of ferromagnetic materials, which occurred during the formation of the Solar System. We show that the magnitude of the magnetic field of the Earth and a change of magnetic field polarity can be explained by the gyromagnetic effect. In the beginning of formation of the Solar System the prospective Sun was the main attractive center. Therefore, there is a possibility that the Sun contains a massive (relative to the Earth) iron-nickel core.

Key words: magnetic field – generation mechanisms – iron–nickel core – magnetic moment – angular momentum – gyromagnetic effect

1 Possible Mechanisms of Magnetic Field Generation

This work continues my diploma thesis devoted to magnetic chemically peculiar stars (CP stars), which differ from other classes of stars by strong magnetic fields, peculiar chemical composition and slow rotation (Romanyuk et al., 2009). The peculiarities of their special origin and evolution may be responsible for such differences. One of the ways to solve this problem is to clarify the mechanisms of magnetic field being generated in the stars. At present two mechanisms are usually considered in astrophysics, viz. a fossil field hypothesis and turbulent dynamo theory. By the fossil field we mean the Galaxy's magnetic field available at the moment of star formation. The lines of force of this field are assumed to be frozen in the primary plasma, with the magnetic field increasing as the plasma is compressed. But the electric current supporting the magnetic field had to stop due to energy losses on the ohmic resistance and hydrodynamic viscosity, since the plasma conduction is high but finite. It is difficult to believe that the magnetic field has been frozen into the plasma for billions of years.

Besides, the fossil field hypothesis does not explain wide variations in the magnetic fields of different stars. The second possible mechanism is a turbulent dynamo. There are a lot of studies devoted to this mechanism. Some of them suppose that all the magnetic phenomena in astrophysics may be explained by this mechanism. But we failed to find a work wherein a possibility of field generation by this mechanism had been shown in principle.It is evident that the dynamo mechanism can create a magnetic field as well as the fields could be strengthened by the turbulent dynamo. However, the present state of the art of these approaches allows neither the possibilities nor limits of their application to be determined.

For example, any effort to explain the Earth's magnetic field by the turbulent dynamo mechanism contradicts the fact that the lava flow velocities are $\nu \sim 5-50\,\mathrm{mm/year}$ (Vainshtein et al., 1980). It is evident that the Coriolis forces are negligibly small at such velocities. Moreover, the characteristic time tx is too long and violates the condition of turbulent dynamo model applicability $t_x \ll t_0$, $t_0 = \frac{L^2}{D}$ (Grigoriev et al., 2003). Here L is the characteristic scale of the process, $D = \frac{c^2}{4\pi\sigma}$ — the diffusion coefficient, c — the speed of light, σ is the medium conduction. For the Earth $L \sim 6 \cdot 10^8$ cm, $c \sim 3 \cdot 10^{10}$ cm/s, $\sigma \le 10^{16}\,\mathrm{s}^{-1}$, $t_0 \sim 6 \cdot 10^{13}$ s, the characteristic time of the process $t_x \sim \frac{L}{\nu} \sim 4 \cdot 10^{15}$ s.

Thus the fossil field hypothesis and dynamo mechanism cannot explain all the problems related to the magnetic fields in astrophysics. It is necessary to consider other possibilities. The magnetic field in a spherically symmetric object may be also generated by a rotating radial electric field if the pressure depends on the depth (Grigoriev et al., 2003). But this mechanism does not explain a change in the magnetic field polarity. All mechanisms considered above are based on Maxwell's equations. The equation $div(H) = 0$ describes the property of magnetic field lines being closed on themselves, hence all the mechanisms of magnetic field generation are described by the equation:

$$rotH = \frac{1}{c}\frac{\partial E}{\partial t} + \frac{4\pi}{c} j \tag{1}$$

In the framework of Maxwell's equations, the magnetic field is generated either by an electric current or by a variable electric field. But there is another mechanism of magnetic field generation.

2 Gyromagnetic Effect and Magnetic Fields of the Solar System's Objects

All elementary particles including the most abundant, i. e. the protons, electrons, neutrons, have their own angular momenta and the corresponding magnetic moment. Microscopic magnetic fields are determined generally by these magnetic moments. These microscopic magnetic fields conventionally vanish in averaging over large volumes. However, a magnetic field may be generated providing their angular momenta are aligned, as has been proved experimentally by Barnett, Einstein and de Haas (Landau & Lifshits, 1982). The magnetic moments, being aligned, produce angular momenta (gyromagnetic phenomena). These phenomena are most conspicuous in the experiments with iron. It is common knowledge that iron is the main ferromagnetic element. It strengthens weak magnetic fields by several orders and remains magnetized even after removing the initial magnetic field. Besides, iron is the sixth in abundance in the primary solar plasma (Ryzhov, 1998).

Now we have reliable data for the magnetic fields of the Solar System's objects and their structure. But the magnetic field generation problem has not yet been solved for planets (Sorokhtin, 1998; Adushkin & Vityazev, 2007). Analysis of the data on the inner structure of planets and their satellites, and their magnetic fields shows that all the large bodies of the Solar System have both

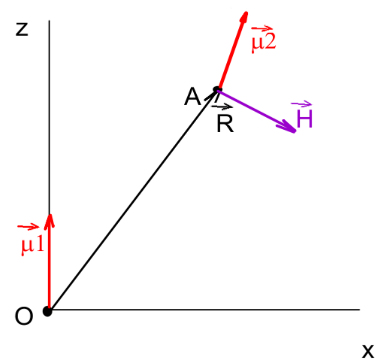

Figure 1: Interaction of magnetic moments

an iron-nickel core and a magnetic field. The magnetic field is proportional to the planet's core volume and its rotational velocity. Jupiter and Saturn possibly have a layer of metallic hydrogen which contributes to an increase in the magnetic field. The existing theories of the Solar System formation do not provide a satisfactory explanation for the fact that the iron–nickel core formed is precisely an iron–nickel one. Meanwhile, it can be explained by the magnetic properties of iron.

3 Magnetic and Gravitational Forces Acting on Particles in Protoplanetary Cloud

Consider two point particles with the masses m_1, m_2 and the magnetic moments μ_1, μ_2 (Fig. 1). We suppose that particle 1 is fixed at the origin of the coordinates. Let $\vec{R}$ be a radius vector of point A, then magnetic field $\vec{H}$ at point A is given by the formula:

$$\vec{H} = \frac{3\vec{n}(\vec{\mu_1}\vec{n}) - \mu_1}{R^3} \tag{2}$$

Here $\vec{n}=\frac{\vec{R}}{R}$. The angular momentum $\vec{K}$ acting on particle 2 located at A:

$$\vec{K} = \vec{\mu_2} \times \vec{H} \tag{3}$$

This moment will turn the particle so that $\vec{\mu_2}$ becomes parallel to $\vec{H}$.

Since the magnetic field is inhomogeneous, in addition to the moment, particle 2 will be subjected to the force:

$$\vec{F} = \nabla(\vec{\mu_2}\vec{H}) \tag{4}$$

Let particle 2 be on the z–axis, then the field at A is in the z–direction, $H_z = \frac{2\mu_1}{R^3}$ and the force acting on particle (2) is equal to

$$F_z^m = \frac{\partial(\frac{2\mu_1\mu_2}{R^3})}{\partial z} = -\frac{6\mu_1\mu_2}{R^4} \tag{5}$$

If particle 2 in on the x–axis, then the field created by particle 1 is in the z–direction and equals $H_z = -\frac{\mu_1}{R^3}$. Particle 2 is subjected to the force:

$$F_x^m = \frac{\partial(\frac{\mu_1\mu_2}{R^3})}{\partial x} = -\frac{3\mu_1\mu_2}{R^4} \tag{6}$$

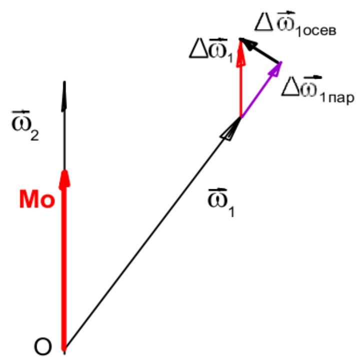

Figure 2: Angular momentum in relative motion

(The partial derivative $\frac{\partial}{\partial z}$ is equal to zero at this point due to symmetry relative to the plane $z=0$). Compare the magnetic and gravitational forces acting on particles:

$$F^G = \frac{\gamma m_1 m_2}{R^2} \tag{7}$$

It is evident that

$$\frac{F^m}{F^G} = \frac{3\mu_1\mu_2}{\gamma m_1 m_2 R^2} = \frac{R_0^2}{R^2} \tag{8}$$

where $R_0 = \sqrt{\frac{3\mu_1\mu_2}{\gamma m_1 m_2}}$. At small distances between the points $R < R_0$ a magnetic force exceeds the gravitational one. The magnetic moment increases only while incorporating iron atoms in a particle, but the mass increases due to any impurities. Thus, the maximum possible value of R_0 corresponds to an interaction of two iron atoms. In this case we have obtained: $R_0 \sim 7\,\text{km}$. While interacting, an iron atom and a body with the mass and the magnetic moment equal to those of the Earth, we have $R_0 \sim 40\,\text{m}$.

Thus, it is reasonable to suppose that early in the formation of the Solar system the magnetic materials were quickly concentrated in the chondrite–type bodies. The latter, mainly consisting of iron, formed the kernels of protoplanets. When their sizes became comparable with R_0, magnetic interaction became inefficient. However, these bodies were more massive than the remaining material of a gas–dust cloud. Given the drag force, in the gravitational field more massive bodies fall faster than those which are less massive. Thus, the protoplanetary cores obtained an additional quantity of iron. Since the magnetic moments of two magnets being combined are added, the planet cores appeared magnetized already at their formation. Besides, this magnetization could increase due to a gyromagnetic effect, which was reflected in the correlation between the angular velocity of a planet and its magnetic field.

4 Earth's Magnetic Field and Gyromagnetic Effect

There arises a question whether it is possible to explain the presence of the Earth's magnetic field by this mechanism. The mass of a firm core equals to about 0.1 of the Earth's mass or $6 \cdot 10^{23}$ kg. So it contains approximately $\frac{6 \cdot 10^{23}}{10^{-25}} = 6 \cdot 10^{48}$ iron atoms. The observed magnetic moment of the Earth is equal to $7.8 \cdot 10^{22}\,\text{A} \cdot \text{m}^2$ and it could be created by adding the spin magnetic moments of $\frac{7.8 \cdot 10^{22}}{10^{-23}} = 7.8 \cdot 10^{45}$ electrons, i. e. a thousandth of the available ones. It means that the existing magnetic moment of the Earth, in principle, can be explained by the gyromagnetic effect.

The Earth's magnetic field polarity is known to have changed. Does the possibility of such a change exist in terms of the gyromagnetic effect? Consider a "free gyroscope", such that all the forces acting on it are applied at its center of mass. Let it rotate around the vertical z axis which does not coincide with the axis of its proper rotation, possibly not intersecting with it. Then suppose that the z axis is an axis of the proper rotation of a body, the moment of inertia of which by far exceeds the gyroscope's moment of inertia. Let $\vec{M}_0$ be an external moment applied to the system, point O laying on the z axis (Fig. 2). The angular momentum change theorem reads

$$\frac{d\vec{K}_o}{dt} = \vec{M}_o, \tag{9}$$

where

$$\vec{K}_o = (J_0 + J_{oz})\vec{\omega_2} + J^R_{cz1}\vec{\omega_1} \tag{10}$$

Here J_0 is the body 2 moment of inertia,
$J_{oz} = mh^2$ — the moment of inertia of the gyroscope about the z axis (h is the distance from the center of mass to the z–axis),
$J_o \gg J_{oz}$,
$\vec{\omega_2}$ —the angular velocity of rotation around the z axis,
J^R_{cz1} —the moment of inertia of the gyroscope about the $z1$ axis passing through the center of mass C,
$\vec{\omega_1}$ is the angular velocity of "proper" rotation around the z axis.
Then the angular momentum change theorem takes the form:

$$(J_0 + J_{oz})\frac{d\vec{\omega_2}}{dt} + J^R_{cz1}\frac{d\vec{\omega_1}}{dt} = \vec{M}_0 \tag{11}$$

Since the first term describes an $\vec{M}_0$— directed vector, then $d\omega_1$ in the second term should be $\vec{M}_0$–directed too. Therefore, $d\omega_1$ should consist of two parts: $\Delta\omega_{1par}$ parallel to $\vec{\omega_1}$ and $\Delta\omega_{1axis}$ perpendicular to $\vec{\omega_1}$. It is the latter that results in two axes coinciding. The external moment $\vec{M}_0$ may be provided, e. g., by collisions with asteroids. But even if $\vec{M}_0 = 0$, the angular velocity of proper rotation can change. In this case (11) may be written in the form:

$$d\vec{\omega_1} = -\frac{J_0}{J^R_{cz1}}d\vec{\omega_2}, \tag{12}$$

where J_0 is the Earth's moment of inertia about its proper axis, J_{cz1} is the electron spin moment of inertia. If the Earth's moment of inertia changes (e. g. due to lithospheric plate motions), we shall obtain from the angular momentum conservation law: $\vec{\omega_2}dJ_0 + J_0 d\vec{\omega_2} + J_{cz1}d\vec{\omega_1} = 0$;

$$d\vec{\omega_1} = -\frac{\vec{\omega_2}dJ_0 + J_0 d\vec{\omega_2}}{J_{cz1}} \tag{13}$$

It means that the angular velocity of proper rotation of the electron will vary both in direction and magnitude. Therefore, the gyroscopic effect takes place even if the external moment $M_0 = 0$. Early in the Solar System formation the proto-Sun was the main attractive center where a massive iron–nickel core (as compared to the Earth's mass) should have been be located.

As a supporting evidence for this fact the following the phenomenon recently discovered (Bonanno et al., 2002; García et al., 2007) may serve: "The analysis of the data obtained by the SOHO mission has proved that rotation velocity near the center of the Sun is essentially higher than on the surface"; "There are some signs of presence of a primary or, at least, very long–living magnetic field below the bottom of the convection zone — in the zone of radiative transfer of energy and in the core".

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