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Influence of the variable magnetic field of the Sun on formation of the protoplanetary disc

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Abstract. This paper discusses a model of the planet formation which is based on the concept of resonant coupling between the solar magnetic cycle and the evolution protoplanetary nebulae. Unlike constant magnetic field, the influence which on plasma is reduced, basically, to pulling material from circumsolar space and redistribution of the momentum of the rotation between protoplanetary disk and central body, variable magnetic field creates the detached orbits, where the agglomeration of material can occur, afterwards it can result in forming the planets. It is shown that shaping the orbits of Jupiter and Saturn could be conditioned under the influence of the variable magnetic field of the solar magnetic cycle with the period $T \sim 24$ years on conducting gas-dust cloud.

1 Introduction

For today in cosmology of solar system origin there are some problems. One of them is the question of explanation of Tatiusa-Bode rule. It is supposed, that the Sun and planets have been formed from uniform protoplanetary nebulae. Initial rotated system contained two or more solar masses, and about half of the mass has been lost (Cameron, 1962). Owing to turbulence, the mass of substance nebulae move from a rotation axis, carrying away surplus of the angular momentum. Other approach to explain angular momentum redistribution is attraction of magnetic field. As a rule, such evolution of magnetic field in protoplanetary disk (the Sun and planets formed out of this disc) is considered (Hoyle, 1960). It is supposed that the magnetic field initially was present int plasma.

The different rotation rates of the central body and external disk resulted in increasing an azimuthal component of magnetic field, increasing angular momentum of the protoplanetary disk and delay of central body rotation. Tight magnetic spiral puts outward pressure upon gas. Simultaneously gas spires outside, while planetosimales move inside (Hoyle, 1960; Safronov, Ruzmaikina, 1985).

The regularity in location of the planets of the solar system in location of the orbits of the planets, displayed by rule of Tatiusa-Bode, represents special interest. This regularity is considered to appear as a result of gravitational perturbations and bursts. At the same time magnetic field could play a significant role in the formation of the planets. It is necessary to examine the the effects of the variable magnetic field. In this article affecting variable magnetic field is considered. Solar magnetic cycle could be a source of variable magnetic field.

2 Influence of a solar magnetic cycle on formation of planets

Formation of solar system occurred in rotating protoplanetary disk consisting of gas and dust. At the initial stage formation of the central body (the Sun) took place. The substance of protoplanetary disk had high mobility and high turbulence. The disk could be heated up because of the interfusion of the areas with various angular velocity of rotation. During the movement of substance on a spiral to the central object, half of gravitational energy turns into kinetic energy, and the other half goes on heating (Ostile and Carroli, 1996). It could result in heating and partial ionization of atoms and molecules of protoplanetary disk. The stream of a high energy galactic particles and rigid radiation of the Sun were sources of ionization. This led to photoionization of atoms and molecules. If high conductivity plasma is present in the disc, any magnetic field, penetrating it, will be frozen in protoplanetary nebula. The Keplerian movement in the protoplanetary disk will try to strengthen magnetic field and to create a shear that results in occurrence of azimuthal magnetic field. On condition that plasma possesses high conductivity, the magnetic field will grow until the disk does starts to rotate together with magnetic lines, or while magnetic field lines will not become torn for whatever reasons.

The interaction of variable magnetic field with protoplanetary cloud plasma should occur during the period of time equal to the solar magnetic cycle. It is possible in case where the residual magnetic field perceived by plasma, will be kept for a commensurable time interval. The dissipation time of magnetic field in plasma with small magnetic Reynolds numbers is determined by diffusion equation $\partial B/\partial t = \eta\nabla^2 B$, where η — magnetic diffusion coefficient which means that variations of magnetic field with characteristic scale l_0 disappear for characteristic diffusion time: $\tau_d = {l_0}^2/\eta$. For in partially ionization plasmas τ_d is equal to $\tau_d = 1.9 \cdot 10^{-8} \cdot {l_0}^2 \cdot T^{3/2}/(ln\lambda \cdot (1 + \tau_{ei}/\tau_{en}))$ sec, where τ_{ei}/τ_{en} — the ratio of effective times of impacts of electrons with ions and neutral atoms. For hydrogen plasma we have $\tau_{ei}/\tau_{en} = 5.2 \cdot 10^{-11} n_n/n_e T^2/ln\lambda$. In our case for week ionization plasma we have $\tau_d = 3.7 \cdot 10^2 \cdot {l_0}^2 \cdot T^{-1/2} \cdot n_e/n$. For the characteristic size of the protoplanetary disk 10^{12} m, $\sim 10^3 K^o$ and ionization level 10^{-12} dissipation time of magnetic field is about 100 years. Thus, the magnetic field can be kept and, under certain conditions, grow by periods of same solar magnetic cycles. It can result in effective influence of magnetic field to nebulae plasma.

Let us assume that the solar magnetic cycle existed at the earliest stages of existence of the solar system when planets were not formed. The period of the solar magnetic cycle, probably, differed from that of the present time, but during evolution, the period of the magnetic cycle changed as well. Let us consider the mechanisms of interaction between the variable magnetic field and the rotary protoplanetary disc. The mechanism explaining the possibility of existence of detached orbits, where magnetic field can be effectively accumulated and lead to plasma extrusion out of this area. On the whole, one should accomplish a task of nonlinear interaction of the variable magnetic field with rotary protoplanetary disc plasma. Let us apply some simplifying assumptions. We shall take into account that during the solar magnetic cycle a change of magnetic polarity of each solar hemisphere occurs. We will also notice that inclination angle D of the solar spin axis is not strictly perpendicular to ecliptic planes and slopes for the majority of planets make $\sim 5 - 7^o$ (Fig. 1).

In this case, in one half of the ecliptic plane, radial magnetic lines have one direction and in the other half they have opposite direction. In these parts of the ecliptic plane the Sun is visible under different angles D. During the magnetic cycle the direction of magnetic field half-planes will change to opposite. Thus, the rotaries around the Sun plasma, hits in the magnetic field of various polarities (Tlatov, 2000). At large distances from the Sun, force lines of magnetic field have preferentially radial direction B_r. At interaction with the gyred protoplanetary disk, from radial magnetic field there can appear an azimuth component of magnetic field B_φ. The magnitude B can be estimated as $B_\varphi \sim R_{em} B_r$ in the case of constant magnetic fields B_r (Safronov, Ruzmaikina, 1985), where R_{em} — magnetic Reynolds number. If the change occurs slowly, it is possible to accept

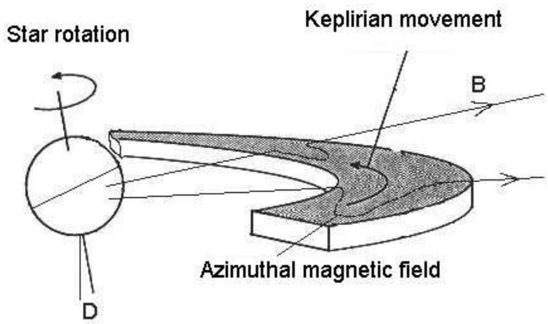

Figure 1: The diagram of shaping azimuthally magnetic field from radial magnetic field in protoplanetary disk.

that plasma and magnetic field are in magnetostatic equilibrium. The pressure of plasma p and components of magnetic field B_φ and B_r are also coupled by relation:

$$0 = \partial P/\partial R + \partial/\partial R(B_r^2 + B_\varphi^2)/2\mu + B_\varphi^2/\mu R - \rho\partial\Phi/\partial R \ , \quad (1)$$

where P — pressure, Φ — gravitational potential, a ρ — density. From this equation it is visible that the growth of magnetic intensity results in pushing out substance. In the case of constant magnetic field, the force of pushing out grows to the disk center. At a variable magnetic field the modification of the component of magnetic field B_φ, is described by the equation:

$$\partial B_\varphi/\partial t = \eta\nabla^2 B_\varphi + R \cdot B_r \partial\omega/\partial R \ , \quad (2)$$

where η — coefficient of magnetic diffusion, R — distance from the spin axis, ω — angular velocity, B_r — magnitude of radial magnetic field. The first term characterizes the rate of dissipation of magnetic field, second - temp of transformation of radial component of magnetic field in poloidal magnetic field. In the case the solar magnetic cycle component B_r is a variable, B_r depends on the phase of the solar cycle and angular position of plasma region. We can assume that $B_r \sim B_{r0} \cdot sin(\theta) \cdot cos(\omega_m \cdot t)$, where $\omega_m = 2/T_m$, T_m — period of the magnetic cycle, B_{r0} — intensity of dipole magnetic field near the Sun, θ — angle between the part of the disk and direction to the center of the Sun. Being rotated on a Keplerian orbit regions of a disk change the relative position concerning solar equator, hence the angle θ will vary, i.e. $\theta = D \cdot sin(\omega t + \psi)$, where a ψ — phase describing the angular position of the region, ω — Keplerian angular velocity of the disk. Thus $B_r \sim B_{r0} \cdot cos(\omega_m \cdot t) \cdot sin(D \cdot sin(\omega t + \psi))$. This relation reflects the change of magnetic field during the magnetic cycle and rotation of the protoplanetary disk around the Sun. For determination of component B_φ it is necessary to carry out integration of equation (2). Let's estimate the first term in the right part of equation (2), time Parker's instabilities (Tout and Pringle, 1992). Let us accept coefficient of magnetic diffusion to be a function of distance from the central body, as well as angular speed of rotation. The diffusion transposition occurs basically through side areas of the protoplanetary disk. We suppose that equation (2) can be written as:

$$\partial B_\varphi/\partial t = B_\varphi/\tau_p + B_{r0} \cdot cos(\omega_m \cdot t) \cdot sin(D \cdot sin(\omega t + \psi)) \ , \quad (3)$$

where τ_p — temporal scale for Parker's instabilities $\tau_p = 2,2 \cdot h_d/v_A$, where h_d — gravitational scale of height, v_A — Alfven velocity for B_φ components of the magnetic field, ψ — phase describing the position of an element, $f(r)$ — function of distance from the central body. The scale of height h_d can be estimated from the isothermal sound velocity and the velocity of rotation of the disk $h_d = c_s/\Omega$. The first term of equation (3) describe the collapse of magnetic field with Parker's instability. The second term describes the growth of the field as a result of transformation of radial magnetic field B_r to the azimuthal field B_φ.

From equation (3) can be seen that the magnetic field differently influences on the protoplanetary substance, depending on the distance from the central body. If one neglects the dissipative term, the integral from the second composed in the formula (3) at $\omega = \omega_m$ is equal:

$$\int sin(\omega_m \cdot t) \cdot sin(D \cdot sin(\omega t + \psi))dt = 2\pi n J(1, D)/\omega_m \ ,$$

where n — an integer, $J(1, D)$ — Bessel's functions of the first kind. From this expression it is visible, that in the period of Keplerian circulation $T = T_m$, the most effective accumulation of magnetic field takes place. In this orbit there is a linear growth of the magnetic field and magnetic pressure. Concentration of particles in nebulae thus should decrease to provide a magnetogasodynamic equilibrium (1). Thus, the substance will tend to abandon the orbit with the period of rotation $T = T_m$. There exist also local maxima in periods $\omega = 2\omega_m$ and $\omega = 3\omega_m$. Note that the dissipative term restricts the time of magnetic field accumulation. Thus, the substance will accumulate where the demagnetization of the plasma disk occurs most rapidly. Let us consider an orbit with period $T = T_m/2$. For this time a complete reversal of the solar magnetic dipole will change the sign on opposite, and the element of the plasma disk will interact with magnetic field of opposite polarity. It means, that the second term on the right side of equation (3) will change to zero in the time equal to the reversal period $\omega = 2\omega_m$. Residual magnetic fields of opposite polarity will cancel each other. The orbit with phase $T = T_m/2$ is preferable to substance accumulation. Now the period of the magnetic cycle is about 22 years. Hence, the orbit on which forces of magnetic ejection on the plasma ring are minimal, is an orbit with a period of about 11 years, i.e. an orbit close to that of Jupiter. If, on the contrary, it is accepted that a substance period in which Jupiter was formed corresponds to half the period of the magnetic cycle, the full period is equal to $T_m \sim 11.86 \cdot 2 = 23.72$ years.

We will introduce an index of magnetic polarity reversals number $Re_m(T)$ of radial components of the magnetic field for a Keplerian orbit with the period T. For this purpose we shall numerically carry out count of quantity of polarity reversals of radial magnetic field $B_r = B_{r0} \cdot sin(\theta) \cdot cos(\omega_m \cdot t)$ in various orbits. The graph of number polarity reversals $Re_m(T)$ on multiplier T/T_m presented in Fig. 2. It is possible to note, that there are special orbits. So, except for period $T = 11.86$ years (Jupiter), there are singularity for periods $T = 29.85, T = 83.02, T = 154.18, T = 248.02$ years. These periods are close to orbits of Saturn, Uranus, Neptune and Pluto. Besides these orbits there are also a singularity for an orbit $\sim 17.8, 33.58$ years and others.

Probably, at the beginning, as a result of substance ejection form orbits $T_m = 23.72$ years, Jupiter and Saturn — two most massive planets of the solar system, were formed. As it follows from Fig.2, the period $T = 11.86$ $(T = 1/2T_m)$ yeas has a maximum deviation of magnetic polarity reversals index from a smooth curve. The period $T = 29.65$ yes $(T = 5/4T_m)$ on the amplitude of deviations of the index R_m is approximately 2 times less than for the period $T = 33.58$ years $(T = 3/2T_m)$. But, probably, its affinity to the orbit T_m has played a more significant role in formation of a second mass planet of the solar system. Orbits of other planets might have been formed under the influence of the gravitational perturbations of Jupiter and Saturn, and under the influence of the cyclic magnetic field of the Sun. But for all that planets occupied places close to orbits with local extremes of magnetic polarity reversals index R_m (fig. 2).

It is possible to present the periods of orbits of planets of giants and Pluto as multiplying from the period of magnetic cycle T_m.

Values of numbers l and n can be seen in the summary of Table 1. It can be noted that numbers l in the denominator are prime numbers. About orbits of terrestrial planets the index of magnetic

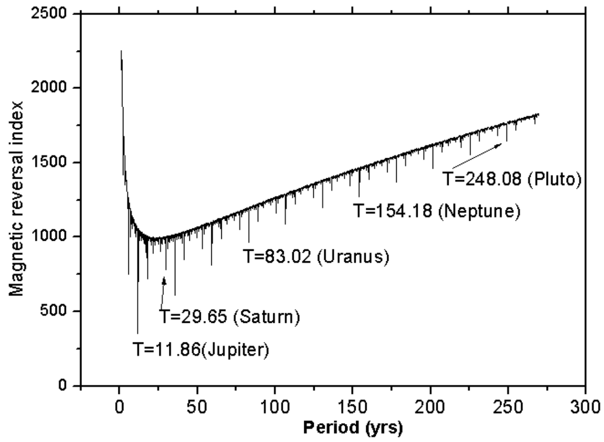

Figure 2: Change of an index of number of magnetic polarity reversals depending on the Keplerian period of an orbit.

Table 1:

Planets	Periods T (years)	l/n	$T_m \cdot l/n$ (years)
Jupiter	11.86	1/2	11.86
Saturn	29.46	5/4	29.65
Uranus	84.01	7/2	83.02
Neptune	164.79	13/2	154.18
Pluto	247.7	19/2	225.84

polarity reversals also has singularity. At the same time, it is more likely that orbits of terrestrial planets have developed under the action of giant planets.

Thus, it is possible, that the solar magnetic cycle exerted a considerable influence upon the formation of the solar system. Two largest planets of the solar system — Jupiter and Saturn — are located near an orbit from which there was n effective replacement of substance by a variable magnetic field. Probably, after termination of formation of these planets their gravitational perturbations have generated planets in orbits aliquot to their periods. If one accepts this hypothesis, it is possible to make a conclusion, that the period of a solar magnetic cycle at early stages of evolution of the solar system was close enough to the present Hale period of the magnetic cycle.

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