Modeling of solar magnetic field using the kinematic-gravitational ion dynamo model

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Abstract. In present article the kinematic-gravitational ion dynamo model accounting for influence of tidal forces on electric currents in ionized substances is applied to modeling of the magnetic field of the Sun. Estimates of currents and field values obtained using a seven-layer model indicate that tidal forces influence is not insignificant. A correlation method for assessment of the Sun’s polarity was created and applied for a detailed analysis of the polarity of magnetic field of the Sun in the 21 and 22 cycles.

1. Introduction
Over the course of the century that has passed since Larmor [1] first introduced the necessity of a self-excitation mechanism to explain the strong solar magnetic field many models and variations of such mechanisms were studied by various researchers. Overview of these works can be found in [2-4]. One of the recent relevant works [5] investigates the model of a tide-synchronized solar dynamo of the Tayler-Spruit type, which is generated by a differential rotation similar to the one found on the Sun. The effect is assumed to be periodically modulated by the tidal influence of the planets and the periodic alignment of the planets with strongest tidal influence: Venus, Earth and Jupiter, on the solar dynamo is noted. Typical appearing dynamo modes are dipoles oscillating with a period of 22.14 years or pulsating with a period of 11.07 years, alongside quadrupole fields with corresponding periods.

With tidal forces enabling this synchronicity, based on the work [6], the main component of solar magnetic field arises from internal sources of solar instabilities (differential motions, thermal and magnetic diffusions) and is a variant of an electron dynamo. In ionized substances both electrons and ions contribute to current generation. If a system has locally heterogeneous distribution of electric charge and is deformed by tidal forces of external objects, its rotation will result in circular currents, capable of initiating the generation of magnetic field. This mechanism is used as a foundation for kinematic-gravitational ion dynamo model [7].

Previous studies of the kinematic-gravitational ion dynamo model for the planets of the Solar system [7, 8, 14], it is shown that the largest tidal forces are generated in the equatorial region of the planet’s core. This predetermines similar mechanisms for the formation of currents that generate the Earth’s magnetic field in the ionized core. For each planet, an estimate of the maximum tidal force was calculated. It is proportional to the mass of the planet’s satellite, its radius, and inversely proportional to the cube of the radius of the satellite’s orbit and the period of the planet’s axial rotation relative to
the satellite. These works show a linear dependence (with a correlation coefficient of 0.997) of the magnetic field of the planets and the tidal forces created by their satellites for the planets of the Solar system. Thus, using the kinematic-gravitational ion dynamo model explains the features of the magnetic field of the planets of the Solar System. Additionally, while solving the inverse problem of magnetometry using IGRF-2005 data [14], an estimate of the plasma velocity equal to \(10^{-4}\) m/s and the share of uncompensated charges per unit of volume equal to \(10^{-7}\).

This suggests that a similar kinematic-gravitational ion dynamo mechanism works for solar magnetic field generation as well. The precondition that enables it is the uncompensated charges of solar atmosphere [10] and the differential and toroidal substance flows in the Sun and heliosphere [5, 11]. The relative velocities of plasma flows near the solar surface reach values of 50-70 m/s [15].

The main aims of this paper include establishing a numerical model to analyze currents and magnetic fields in ionized substances within the kinematic-gravitational ion dynamo framework, and investigate its consistency with observed data on variation of solar magnetic field.

2. Layered model of solar magnetic field generation

Based on the estimates of the solar structure parameters [13], using the models from [14], parameters for seven layers of the Sun: coronasphere, chromosphere, photosphere, and four layers of the convective zone are calculated (table 1).

| Relative radius | Particle density (1/m³) | Volumetric charge (1/m³) | Current per surface unit (A/m²) | Current in a layer (A) | Magnetic field of a layer (Gauss) |
|-----------------|-------------------------|--------------------------|-------------------------------|------------------------|---------------------------------|
| 1.02            | 1.000e-007              | 5.975e+019               | 9.572e-012                    | 9.572e-011             | 1.332e+003                     | 1.060e-001                     |
| 1.00            | 7.400e-005              | 4.421e+022               | 7.084e-009                    | 7.084e-009             | 9.853e+004                     | 7.841e+000                     |
| 0.98            | 1.000e+000              | 5.975e+026               | 9.572e-005                    | 9.572e-010             | 5.326e+004                     | 4.238e+000                     |
| 0.90            | 2.000e+001              | 1.195e+028               | 1.914e-003                    | 1.914e-009             | 1.332e+005                     | 1.060e+001                     |
| 0.80            | 9.000e+001              | 5.377e+028               | 8.615e-003                    | 8.615e-010             | 5.992e+004                     | 4.768e+000                     |
| 0.70            | 2.000e+002              | 1.195e+029               | 1.914e-002                    | 1.914e-010             | 1.332e+004                     | 1.060e+000                     |

It is assumed that the layers are predominantly made up of hydrogen. Performing the simulations for a range of values of volumetric charge. (ratio of uncompensated elementary charges to the total number of atoms in a unit of volume, VC) the following result is obtained:

For VC=\(10^{-7}\) for the upper layer and at VC=\(10^{-12}\) for the remaining layers, at relative velocities ranging from 100 m/s for the upper layer to \(10^{-8}\) m/s for the lower layer, the maximum currents and magnetic fields are provided in table 1.

As follows from these estimates, based on kinematic-gravitational ion dynamo model, all model layers, under favorable conditions can participate in generation of magnetic field.

The generation process intensifies with the number of sunspots. This can be explained by an increase in flux velocity. Changes in the number of sunspots, amplitude of solar magnetic field and their relation are illustrated by (figure 1). To analyze and interpret anomalies of magnet field of the Sun caused by deep plasma flows, the derivation of formulas and calculation of the change in the
tangential to the solar surface velocity is used, depending on the displacement dR equal to the height of the volume of substance rising along the radius in the Coriolis model. Initially, let’s calculate the absolute linear velocities of the gravitational trace of planets along the Sun's surface:

\[ V = \frac{2 \pi R}{T} \]

where T is the relative period of revolution of the planet around the Sun.

For Earth \( V = 2022 \) m/s, for Venus \( V = 1,950 \) m/s, for Mercury \( V = 1516 \) m/s.

To account for the fact that the observations are made from Earth, the velocity of 2022 m/s corresponding to the 27 day period of the Sun's axial rotation relative to Earth, will be taken as the average in the interval of the minimum SA (SA).

Let us introduce a single-layer model in the equatorial region. The upper boundary of the model coincides with the solar surface with relative radius \( R_1 = 1 \) and the second with an undetermined radius. At a minimum of SA the velocities of points on the equator of the rotating ball are equal:

\[ V = \frac{2 \pi R}{T}, \]

with \( V_1, V_2 \) for velocities corresponding to \( R_1 \) and \( R_2 \), we obtain

\[ \frac{V_2}{V_1} = \frac{R_2}{R_1}, \quad V_2 = \frac{R_2}{R_1} V_1, \quad dV_2 = \frac{V_1 \cdot dR_2}{R_1}. \]

This formula allows us to estimate the comparative changes in velocities with respect to changes in the depth of the flow, assuming that equatorial flow located at 0.8 radius moves towards the surface with \( V_1 = 2022 \) m/s and \( dR_2 = (0.8 - 1) = -0.2 \) we obtain:

\[ dV = \frac{-2022 \cdot (-0.2)}{1} = 404.4. \]

A positive estimate of the Coriolis velocity corresponds with the relative clockwise motion of flows rising to the surface. In the equatorial region, this velocity reaches the greatest values. Poloidal and toroidal currents, are constantly created in the upper layers and atmosphere of the Sun, directed clockwise if viewed from the northern pole, of internal quasi-periodic processes and external gravitational sources, with influence from Coriolis forces. This motion of weakly charged plasma is included in the current generating solar magnetic field. Below we provide an estimate of the relative level of the increase in the velocity of the flows corresponding with maximum magnetic field caused by the rising flows from the convective layers of the Sun. The estimate is derived from the magnetogram of cycle 21, plotted from daily observations of the of the Sun's magnetic field according to data from the Wilcox Solar Observatory from 1975 to 2015.

3. Analysis of deep flows

Between 1977 and 1982, three ascending plasma flows were identified. First and second have velocity estimates of 44 m/s and 39 m/s. It can be assumed that the second flow continues the first, and they reflect a single process of mass upwelling lasting more than four years. At low longitudes in July-September 1982 we see a fragment of a third, high-speed flow (\( V = 161 \) m/s). It can be assumed that it is generated from the lower part of the upper convective layer, judging by its velocity. so, the radius of the bottom of the active layer is close to 0.9. Close to maximum of SA plasma fluxes can flow from the photosphere into the chromosphere and coronasphere. Each of the deep plasma flows, therefore, generates magnetic field and, at the same time, decreases the velocity of the solar layers in question.
The veracity of the model of solar magnetic field generation is supported by the following observations: the axial rotation rate at different latitudes varies within 20% [15] and a negative correlation between the magnetic field and rotational speed is established [16, 12, 17].

The influence of the planets on the Sun is proportional to their gravitational potential [11, 18] with the following relative values: Jupiter 2.26, Venus 2.2, Earth 1, Mercury 0.92. Saturn 0.11. Gravitational influence on the processes is considered additive, so the maximum occurs when all the planets are on the same side of the Sun, close to the line connecting the Earth and the center of the Sun. The minimum is recorded from the Earth when the major planets are on the opposite side of the Sun from the Earth, where their observed influence is counteracting the generation of magnetic field.

Due to the synchronous behaviour of solar magnetic field and solar spots under the influence of the same forces, the linear dependence of these parameters emerges. According to the data of Cycle 21, the relation is:

\[ A = 10 + 0.17N \]

where \( A \) - is the amplitude of the calculated trend of MF absolute values, \( N \) - the trend of the Wolf number, obtained by smoothing on the basis of 81 days (three solar revolutions).

The Wolf numbers and absolute values of MF are depicted on figure 1 (a and b). The calculated estimates and smoothed estimates from real data agree in the long-period range, but there are local deviations in half a year intervals, the significant ones manifesting themselves in 1979 and 1982 under the influence of external sources.

4. Analysis of polarity of magnetic field of the sun

At the final stage of the study, differences in inclination angles between the orbital planes of planets relative to the plane of solar equator were accounted for. In (figure 1d) the angles of inclination of the trajectories of the planets relative to the plane of the sun's equator (PES) are depicted as: Jupiter – blue line, Saturn - grey line, Earth – black line. The trajectories of the planets are calculated using the astronomical program Swiss Ephemeris taking into account the gravitational pull of all the planets of the Solar system, this accuracy is important for calculating the trajectory of the Earth.

Jupiter's orbital trajectory crosses the solar equatorial plane in January 1977 and reaches its highest point in the northern hemisphere in 1980 - 1981 and crosses the equatorial plane of the sun again in 1983, so Jupiter for 6 years and Saturn for 11 years are above the equatorial plane of the sun, which creates conditions for the generation of dipoles directed from north to south in the northern hemisphere, dominating in amplitude over the southern.

Comparing the graphs of the Earth's trajectory and the averaged values of solar magnetic field, we see that during three years (1976-1978) the southern part of the Earth's trajectory corresponds to positive anomalies, and the northern - neutral. Since 1979, positive anomalies are registered in the northern part of the trajectory, and negative anomalies in the southern part since 1981.

The reasons for the formation of magnetic field anomalies are the planetary tidal forces, contributing to the acceleration of rising to the solar surface flows, caused by internal forces. At the same time, on the opposite side - in this example, in the southern hemisphere, the planetary tidal forces contribute to the slowing of the motion of masses to the surface and weakening of the magnetic field generation processes in the southern hemisphere. Therefore in the southern hemisphere, the northern hemisphere return lines of force will prevail, and they are recorded in the southern hemisphere in 1980 and 1983-1988.

During the SA maximum, plasma fluxes burst outside the photosphere and, with the participation of the planetary tidal forces, create strong magnetic field anomalies in the chromosphere and coronosphere, which can increase or decrease up to the reversal of polarity, as happened in 1982.
An algorithm and program were created to calculate the polarity of the Sun, based on the correlation of a given interval of the Earth's trajectory to the smoothed values of the solar magnetic field intensity observed from the Earth. Figure 1b depicts a graph of the averaged solar magnetic field values, and figure 1e – the result of the correlation in timeframe of 1.5 and 3 years.

The analysis is based on a more detailed graph (figure 1e). In the initial period, both graphs are below the zero line, which corresponds to the negative polarity of the Sun formed in cycle 20. Completing the negative phase in 1979, the graphs cross the zero line and follow at 0.4 for 1.5 years. After 1981, the graph shows an excursion into the negative area during the year. The minimum of -0.4 is registered late in 1981. In the first half of 1982, the graphs begin to rise from the zero line. The correlation reaches its highest values (0.8) in 1986, which is consistent with the correlated solar magnetic field and Earth's astronomical trajectory plots.

The five-year period of growth can be explained by the fading of turbulent and compound flows, and consequently, currents and solar magnetic field which decreases by an order of magnitude as the flow attenuates. The rest of the solar magnetic field during the quiescence period is generated with little attenuation by flows preserved in the convective zone.

During the period of intense growth of activity, the Wolf numbers and solar magnetic field absolute values approached the highest level of cycle 22, and as the graphs go down after a year and a half they reach the zero level stay there for about 3 years. From 1992 there is a downward slope to -0.5 and a slight rise to -0.4 by 1998.

A comparison of the features of the graphs suggests that during periods of rapid SA growth, the correlation graphs tend towards or cross the zero line if the gravitational forces of the planets contribute to the reversal of polarity. During the decay period of the SA, the absolute values of correlation graphs decrease smoothly to a certain constant level.
5. Conclusions
1. The influence of internal forces and external gravitational fields of the planets, creates poloidal and toroidal currents of positively charged substance, and consequently generate toroidal and dipole magnetic fields in the outer layers and atmosphere of the Sun.
2. While estimating charge densities, currents and magnetic field strengths, intermediary parameters calculated for seven layers of the Sun suggest that all modeled layers can participate in generation of magnetic field of the Sun.
3. The intensification of the magnetic field generation process by tidal forces is caused by the rise of substance to the Sun's surface, contributing to the solar magnetic field generation and slowing down the velocity of the upper layers of the Sun.
4. Magnetic field of the Sun is generated by internal forces that cause substance to move. External tidal forces of the planets enhance or weaken these processes.
5. Accounting for the differences in inclination angles of planetary orbits compared to the solar equatorial plane a correlation method for assessment of the Sun's polarity was created and applied to a detailed analysis of the solar magnetic field polarity in the 21 and 22 cycles.

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