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On the Precession of the Solar Magnetic Axis

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Abstract—We propose a model that describes the observed behavior of the large-scale magnetic field of the Sun. The model is based on the concept of a current disk of radius $R_\odot$ rotating around an axis frozen in the Sun which passes through its center and which lies in the disk plane. The rotation period of the disk is equal to the 22-year solar period. In particular, the model is consistent with observations of the solar corona, which is considered as a region adjacent to the plane of the current disk (to the equatorial plane of the dipole) extended beyond the Sun.

FORMULATION OF THE PROBLEM

As a theoretical interpretation of a number of large-scale phenomena caused by solar activity, we propose a kinematic model that links these phenomena. The model assumes that the dipole magnetic moment of the Sun is produced by a current disk of radius $R_\odot$ rotating around an axis that connects two points of the equator with Carrington longitudes $\varphi_1 \simeq 0°$ and $\varphi_2 \simeq 180°$. The rotation period is $T_A \simeq 22$ years, and its sense of rotation about vector $\mathbf{A} = (\varphi_1, \varphi_2)$ is given by the corkscrew rule. The magnetic-moment vector **M** is perpendicular to the plane of the current disk and rotates with the same period $T_A = 2\pi/\Omega$ and in the same sense. The visually observed mean plane of the (unperturbed) corona coincides with the current-disk plane and also rotates around axis $\mathbf{\Omega}$, taking twice the solar period, $T_A \simeq 22$ years, to make a complete turn. In a stationary coordinate system, the magnetic moment **M** is involved in the rotation of the Sun about axis $\boldsymbol{\omega}$ that is fixed in space and rotates about axis $\mathbf{\Omega}$ that is frozen in the Sun (Fig. 1). In general, the motion of vector **M** is a kind of precession of a gyroscope axis. Both rotations are considered to be synchronized, and the energy needed to maintain the magnetic field is apparently drawn from the rotational energy of the Sun.

Initially, the solar period was determined by the number of emerging sunspots and characterized by a value of $\simeq 11$ years. With the discovery of sunspot magnetic fields and with allowance for their polarity, it became clear that twice that value should be considered to be the full solar period $\simeq 22$ years. Presently, it is reasonable to assume that the solar cycle is governed by the mechanism of solar dynamo and by periodic variations in the large-scale magnetic field. In turn, the structure of the coronal magnetic field determines the visually observed shape of the solar corona. In any case, periodic variations in the location of the plane of the magnetic equator in space, which coincides with the mean plane of the unperturbed corona and with the plane of the heliospheric current sheet, seems beyond question.

DISCUSSION OF THE MODEL

The simplest kinematic model that we propose is based on the concept that the governing elecromagmetic processes are ideally periodic. In this study, our goal is to construct an elementary scheme that can consistently explain a set of observed phenomena, if all factors affecting the periodicity are ignored.

We take the solar period $T_A = 22.08$, which is a multiple of the rotation period of the Sun $T_\odot = 25.38$ days, to be the basic parameter, so that their ratio (to three significant figures) is an integer, $T_A/T_\odot = 318$ (Allen 1977).

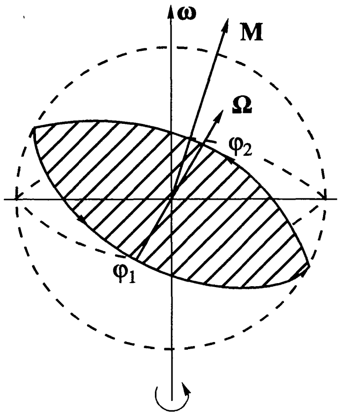

Fig. 1. The location of an $r = R_\odot$ current disk and the dipole moment **M** which rotate about axis $\mathbf{\Omega}$ that passes through the points of the equator with heliographic longitudes φ_1 and φ_2.

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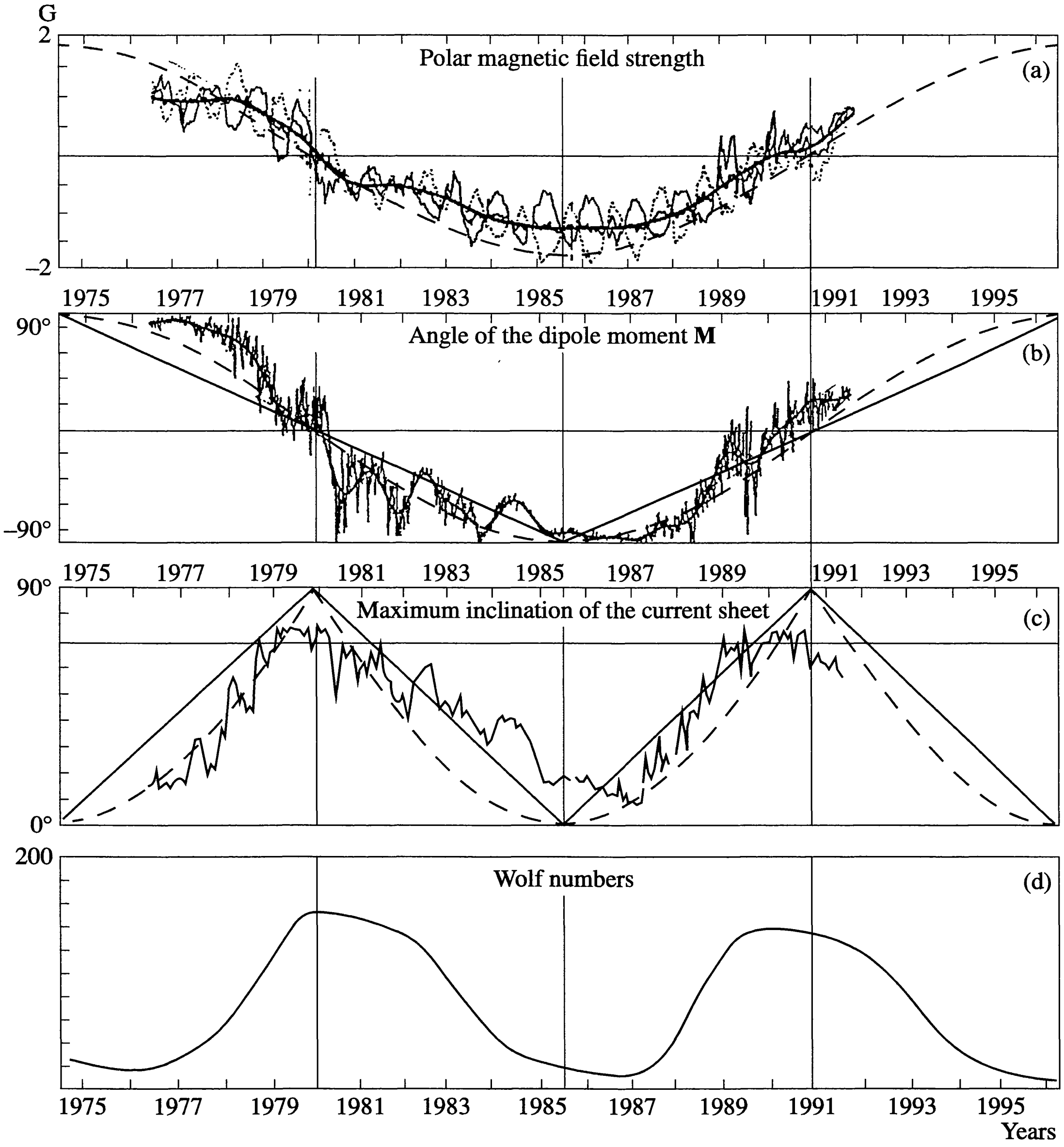

Fig. 2. The polar magnetic field stength (a), the latitude angle of the dipole moment **M** (b), the inclination of the current sheet (c), and the Wolf numbers for solar cycles 21 and 22 versus time. The sinusoid with the nodes at the points 1980 and 1991 and the segments of the straight lines correspond to harmonic oscillations and uniform rotation of the dipole moment about the axis $\mathbf{\Omega}$, respectively. The rotation axis $\mathbf{\Omega}$ is perpendicular to the plane of the figure, and the rotation is counterclockwise.

Figures 2a–2c from Hoeksema (1992) shows the time dependence of the polar magnetic field strength, the latitude angle of the dipole magnetic moment of the Sun, and the inclination of the heliospheric current sheet between 1976 and 1992. We see that the curves describe, with some deviations, a periodicity with a period equal to the full solar cycle, T_A = 22.08 years. Note that since the magnetic moment is perpendicular to the plane of the current sheet, the plot in Fig. 2c must coincide with the plot in Fig. 2b after a mirror reflection of its parts to the left of the 1980 maximum and to the right of the 1991 maximum. Figure 2 also plots the fits—sinusoids and polygonal lines extended backward and forward in time. The sinusoid describes harmonic oscillations about the equatorial plane with a ±90° amplitude, and the polygonal lines describe uniform rotation. The deviation of the initial curves from the fits makes it impossible to unambiguously decide between these alternatives. Below we give arguments for choosing rotation, which is probably nonuniform. The time dependence of the angle of rotation of the dipole moment calls for further analysis.

The behavior of sunspots that are involved in the rotation of the Sun and that migrate toward the equator leads to the natural conclusion that the dipole moment rotates about an axis that is fixed relative to the Sun. Assuming that the dipole component of the magnetic field is produced by a current disk of radius $R_\odot$ with azimuthal currents, we obtain a very simple model with a current disk that rotates around an axis that connects two opposite points of the magnetic equator. The period of this rotation is equal to the full solar period, 22.08 years. Since the currents more likely flow in the vicinity of the photosphere, the current disk can apparently be viewed as a circular current loop located on the magnetic equator. The magnetic-field lines produced by the azimuthal currents form distinctive patterns of the solar corona and the heliospheric current sheet, whose mean planes coincide with the plane of the disk and turn with it.

Figure 3a shows the current disk and the dipole magnetic moment **M** which rotate with the period $T_A = 22$ years about axis Ω in a coordinate system fixed to the Sun. Figure 3b shows regions of the positively and negatively directed normal components of the photospheric magnetic field for various locations of the rotating current disk, which correspond to Fig. 3a. In our approximation, the neutral line, which separates the positive and negative regions, is formed by the intersection of the current disk with the photospheric surface, and the polarity of the magnetic field is determined by the direction of the azimuthal currents in the disk. Thus, the shape of the neutral line and the location of the regions of different polarity unambiguously follow from an examination of Fig. 3a, in which the direction of the magnetic field is indicated by circular arrows. The sequence of maps in Fig. 3b shows the evolution of the positions of the northern (light) and southern (dark) regions of the photospheric magnetic field and the neutral-line shapes on one (fixed) side of the Sun. The corresponding maps can be constructed for the opposite side of the Sun on symmetry grounds. The light and dark regions interchange in latitude when the vector **M** intersects the equatorial plane, which corresponds to a reversal of the polar magnetic field and to a sunspot maximum (see Fig. 2d which shows monthly mean Wolf numbers).

The properly averaged distributions of the normal component of the magnetic field for positions that approximately coincide with the positions in Fig. 3b are shown in Fig. 4, which is taken from Hoeksema and Scherrer (1986) and Hoeksema (1992). A comparison of these figures leads to the following conclusions:

(1) The shape of the neutral lines and the field direction are in satisfactory agreement with the theoretical distributions in Fig. 3b.

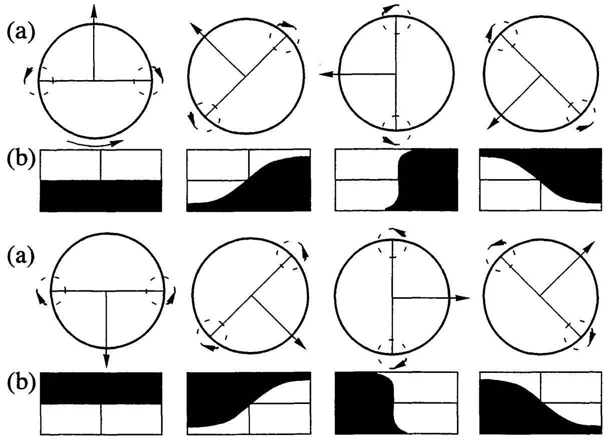

Fig. 3. Sequential locations of the dipole moment **M** and the current disk during a complete turn made in twice the solar cycle. (a) The circular arrows indicate the direction of the magnetic field at the edge of the $r = R_\odot$ current disk (b). The corresponding model distributions of the normal component of the photospheric magnetic field. The light and dark regions of positive and negative field directions are separated by the neutral line determined by the sequential locations of the current disk.

(2) The full set of maps which differ by permutations of the dark (S polarity) and light (N polarity) regions provides evidence for rotation of the current disk rather than oscillations.

(3) A comparison with the theoretical neutral lines indicates that the rotation axis of the current disk is confined to the equatorial plane and passes through the points with Carringron longitudes $\varphi_2 = 180°$ and $\varphi_1 = 0°$.

(4) It follows from an analysis of the time sequence of magnetic-field distributions that the rotation about the axis (0°, 180°) is clockwise. Indeed, the sequence of theoretical distributions corresponds to counteclockwise rotation, and a comparison with the evolution of magnetic-field distributions in Fig. 4 shows that this rotation occurs around vector (180°, 0°), which is equivalent to clockwise rotation about the axis (0°, 180°).

The existence of a current ring in the vicinity of the solar magnetic equator clearly follows from the photographs of the base of the corona (Fig. 5) taken by November and Koutchmy (1994), provided that the circular filaments are interpreted as magnetic-field lines.

The overall picture of the rotating solar corona, which follows from the proposed kinematic model of the magnetosphere, is shown in Fig. 6. The magnetic field at large distances from the Sun is the superposition of the dipole field of a ring of radius $r = R_\odot$ and the field of a large current disk (heliospheric current sheet). Because of the low particle number density at $r \gg R_\odot$, the azimuthal current in the large current disk is apparently produced by the drift of charged particles.

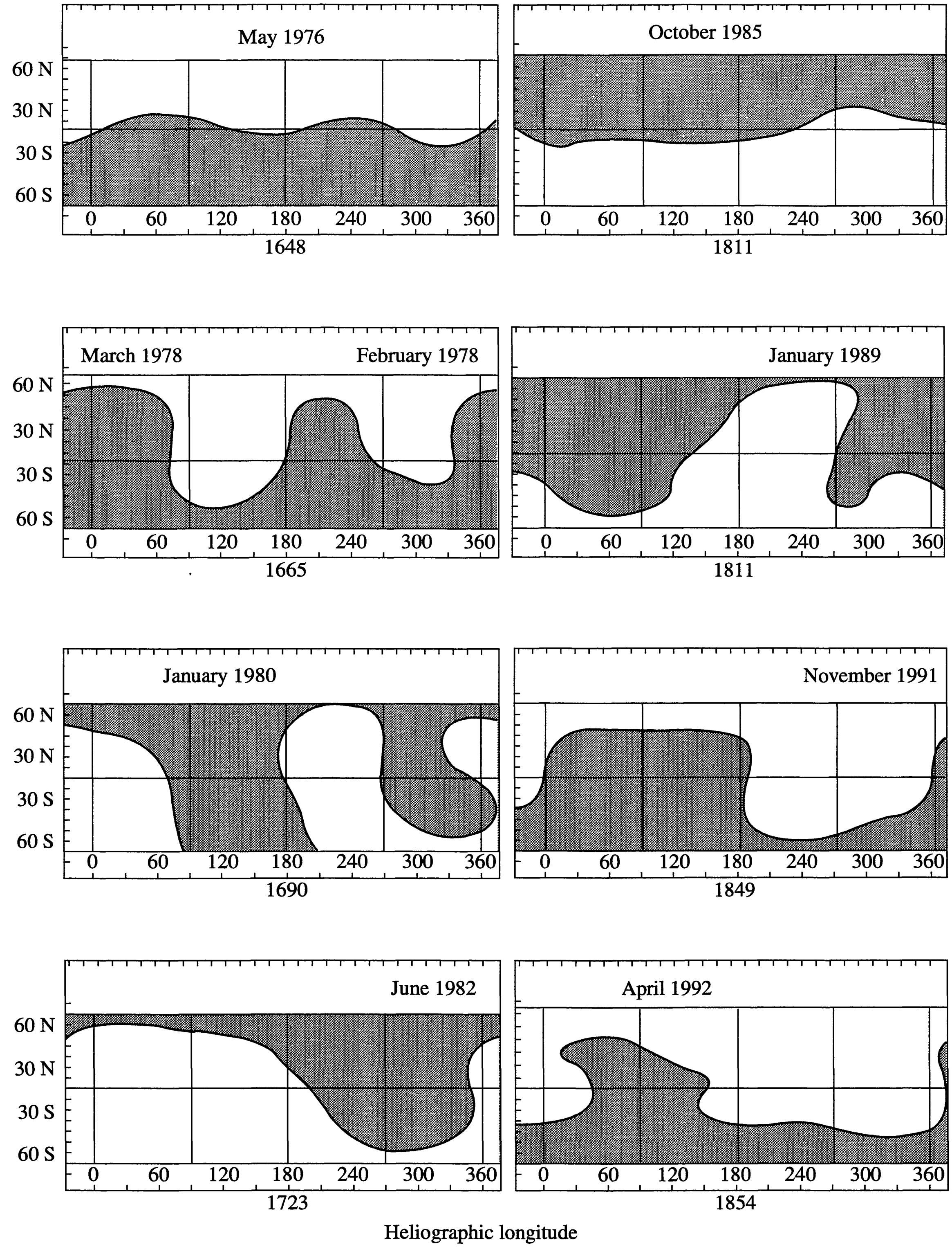

Fig. 4. Averaged maps of the photospheric magnetic field constructed in the interval (0°, 360°) of heliographic longitudes. In the ideal model under consideration, the neutral lines are represented by periodic functions with nodes at the points of the equator with longitudes $\varphi = 0°$ and 180°. A comparison with Fig. 3b shows a satisfactory agreement with the model, if we assume that the maps in Fig. 3b are located in the half-interval (90°, 270°), while the magnetic moment **M** rotates counterclockwise about the point $\varphi = 180°$.

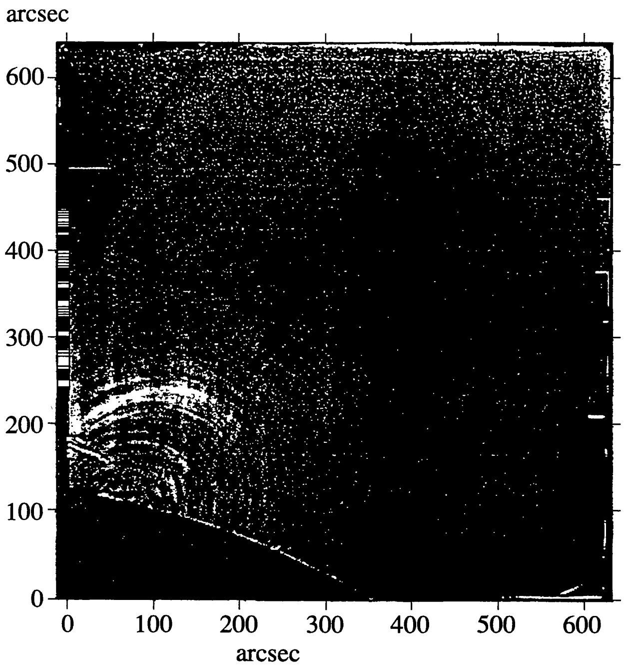

Fig. 5. The pattern of toroidal magnetic surfaces at the base of the solar corona. The set of concentric circumferences represents magnetic-field lines of a current ring with $r = R_\odot$ located on the magnetic equator of the Sun. The dashed lines indicate the outer contours of the helmet structure of the corona.

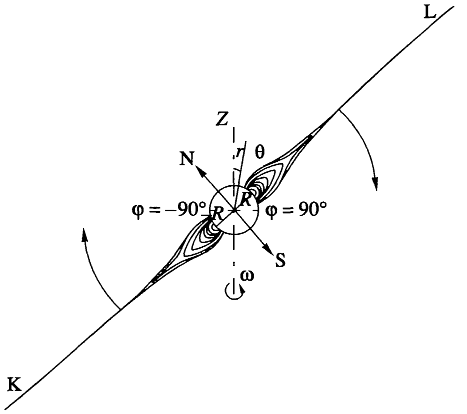

Fig. 6. The general view of the rotating current ring, the heliospheric current sheet, and the solar corona. NS is the solar magnetic axis; RR is the current ring (magnetic equator), $\varphi = -90°, +90°$ is the solar equator, KL is the large current disk (heliospheric current sheet). The solar magnetosphere as a whole rotates clockwise about the axis (φ_1, φ_2) $(\theta = \pi/2, \varphi_1 = 0°, \varphi_2 = 180°$ of the Carrington longitude) with the period $T_A = 22.08$ years; in addition, it is involved in the rotation of the Sun around the z-axis with a period of 25.38 days.

CONCLUSION

The kinematic model that we proposed describes the flow of large-scale currents and the motion of the magnetic field produced by them. This model unequivocally follows from an analysis of the evolution of the pattern of heliospheric magnetic fields with time and may serve as a basis for the construction of alternative theories of solar dynamo. It should be kept in mind, however, that the motion of the photospheric current disk in the model described above can also be a result of time variations in the density of distributed toroidal currents that are fixed relative to the Sun. Note also that our model ignores the influence of the toroidal magnetic field, which may play a significant role in the hydrodynamic processes of solar dynamo.

A similarly formulated problem was considered by Saito and Oki (1989), who calculated the sequence of distributions of the photospheric magnetic field using a model of photospheric magnetic dipoles with different orientations (see also Wilcox and Handhausen 1983; Saito and Akasofu 1987; Gulyaev 1987; Vanyarkha 1995; Gulyaev and Vanyarkha 1995; etc.).

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