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Role of Meridional Circulation System in Origination Sunspot Cycle: A Brief Review

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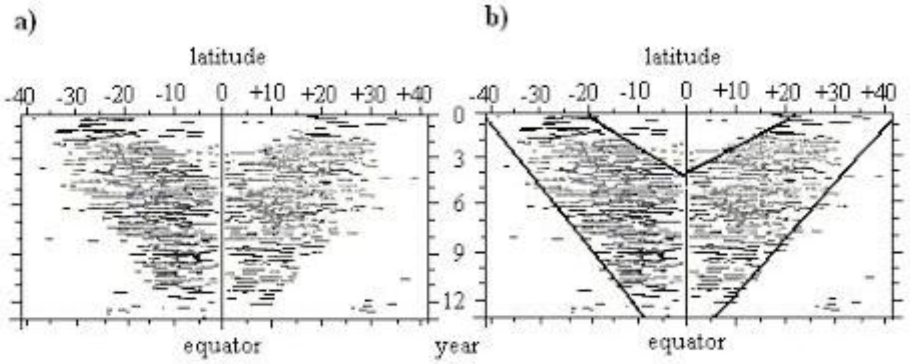
Abstract

Based on the recent helioseismology investigation, an 11-year sunspot cycle model is proposed in this paper, where the period of the cycle is mostly determined by meridional circulation. The annular magnetic field toroids, which are obtained through reconnection of magnetic field near the base of Ω-like loops of the force line tube, are suggested as "embryo" of solar activity. The toroids are transported by meridional flow from middle latitudes to the equator within layers of a depth 0.82>R>0.91, where R is the radius of the Sun. Near the equator, under the effect of the circulation flow, the toroids submerge to the layer of 0.82>R>0.7, where they move to the middle latitudes parallel to the base of the convective zone. In this part of circulation cell, the magnetic field of the toroids is efficiently enhanced by the dynamo mechanism. Next, the enhanced field toroids emerge in the middle latitudes to the layer of 0.82>R>0.91 and complete the cycle by moving towards the equator. Here, just some of the toroids flow to the surface of photosphere forming bipolar groups according to Maunder "butterflies". Hale's law is fulfilled by a 180º reversal of the plane of toroids at each passage of the cycle. For stability, the self-magnetic field of toroids is helically whirled with a force-free current running along the annular axis of the toroids. The main dipolar magnetic field required for the self-sustaining sunspot cycle is obtained as a sum of dipole magnetic fields created by force-free currents of toroids. The model accords well with a whole range of solar activity properties following from observations.

Key words: *1; meridional circulation. 2; sunspot cycle. 3; magnetic toroid.*

1. Introduction

Observations over the last three centuries have shown that solar activity has a cyclic pattern with a period of ~11.2 yr (within the range from 7 to 17 years). The centers of activity (flares, eruptive bursts, hard radiation, etc.) are constituted by sunspots and sunspot groups, where the strongest magnetic fields observed on the Sun (up to 4 kGs) are concentrated. The first sunspot group of the cycle emerges in the latitudes of ~±35° on the both of the Sun's hemispheres, and then the sunspot zone moves towards the equator to ~±5° (Sperer's law). The activity reaches its peak in about 4 years, which is followed by a slower decline to the minimum level (~7 years). Further, a reversal of the polarity of magnetic fields from cycle to cycle, has been observed, where the polarity of the preceding (*p*-) sunspot cycle in a group corresponds to the polarity of the main dipolar magnetic field of the same hemisphere (Hale's law). Besides, near the moment of the activity peak (with a short time delay), the cycle undergoes zeroing of the main dipolar field followed by a polarity reversal. At the end of the cycle, the sunspots reach the ~±5° latitudes and disappear, and the first spots of a new cycle emerge at the latitude ~±35° at about the same time. The sunspot activity can be visualized in a diagram, where latitudes of sunspot origination are plotted along one of the axes, and the time of observations in years, along the other axis. The diagrams are referred to as Maunder "butterflies" due to their characteristic shape resembling the wings of a butterfly (Figure 1a).



a) typical view of the butterfly diagram
b) straight-line approximation of the contour of the wings

Figure 1. Maunder butterfly diagram

In earlier model [Babcock, 1961; Leighton, 1969], Hale's law is ensured by the fact that the lines of force of the main (poloidal) magnetic field, repeated their winding with the Sun's rotation, forming an azimuthal (toroidal) magnetic field for active regions (ω-effect). Yet, it is estimated that the density of azimuthal field could hardly be brought to ~50 Gs in a single activity cycle, whereas sunspots usually feature fields of ~3 kGs, or stronger. Therefore, additional enhancement of azimuthal field is assigned with a "dynamo" mechanism in the Sun's deeper layers (those situated below the convective zone). In the Babcock-Leighton model, at the end of a solar activity cycle, the fragments of groups disappear near the equator through mutual neutralization of fields of different hemispheres. Maunder "butterflies" do not confirm mutual penetration of the fields, but supports that the fragments of active regions disappear near the equator. Still, what makes the biggest problem for the model is that a reversal of polarity of the main dipolar field occurs at the activity peak. At the moment of polarity reversal, the main dipolar magnetic field disappears. Hence, the toroidal field wound with the ω-effect is zeroed, and all the sunspots forming the active areas disappear. Such absence of sunspots on the disk of the Sun can indeed be observed, but only at the period of the minimum of solar activity. At the peak of activity, there are no manifestations of the main field polarity reversal, and the polarity remains reversed throughout the activity decline period.

Development of solar dynamo numerical models is described in a thorough overview by Parker [1979, Ch.21.2 of the monograph]. Parker regards the absence of uniqueness of solution owing to an excessive freedom of choice of physical parameters unknown from observations as one of the shortcomings of the dynamo models. For example, it is possible, by choosing appropriate parameters of non-uniform rotation and turbulent diffusion, to obtain diagrams of latitudes of emergence of active regions with a 22-year period, which would remotely resemble Maunder "butterflies". However, this is achieved with unacceptable deterioration of other dynamo characteristics. The main difficulties of the dynamo theory at explanation of the sunspot cycle properties are also briefly stated by Priest [1982, Ch.9 of the monograph]. In the critical review [Spruit, 2010], numerous theoretical studies on solar dynamo of the last decades are presented as purely speculative schemes only distantly related to observational facts of solar activity. Therefore, it is justified to search for new ideas and approaches to solving the problem of solar activity simulation. Besides, raising the level of our knowledge in this field, such study is relevant from the practical point of view, e.g., for improving the safety of space-flights, forecasting radio communication disruptions, effects produced on the climate and human health, etc.

The objective of the paper is to suggest a model of an 11-year solar activity cycle, which would be the most consistent with observational data including recent results of helioseismological research.

2. Meridional Circulation System

The history of evolution of the idea to bring meridional circulation of matter in explanation of the 11-year solar activity cycle dates back to the earliest years of its exploration. A brief overview of papers on this subject is presented Bray and Loughhead [1965, in Ch.8.4.1. of the monograph]. For a number of reasons, the idea was never further developed, in particular, due to complexity of displacement (with emergence and submergence) of global toroidal fields extending throughout the Sun's latitudes. With introduction of a magnetic-kinematic sunspot cycle model [Leighton, 1969], displacement of the sunspot formation zone could be interpreted as migration of the active region enhanced by the dynamo mechanism. Later, numerous papers made attempts to find wave solutions of equations with a 22-year cycle, yet the results are not satisfactory.

In this paper, the extremely complicated problem of sunspot cycle simulation is proposed to be reduced into two separate but relatively simple subproblems: (i) displacement of active sunspot regions (sunspot groups) under Sperer's law from middle latitudes to the equator with meridional circulation flow and (ii) enhancement of magnetic fields in the interior of the Sun by any (even the stationary) dynamo mechanism to values observable on the surface. Elaboration of the first subproblem makes the primary subject of this paper. The second subproblem is left beyond the scope of its consideration, as it is assumed that, among numerous varieties of dynamo, at least one will be found which is able to enhance the magnetic field of active regions up to a required value. It is assumed that the solar matter emerges up from the interior at the latitude ~±35° and moves in a layer beneath the photosphere along with active regions to the latitudes ~±5°, submerges to the base of the convective zone and keeps moving there to the middle latitudes in parallel to the base. It is in this part of the trajectory that the magnetic fields of active regions are enhanced by the dynamo mechanism to values as high as ~100kGs. Then, the matter with an enhanced magnetic field emerges to the surface at the latitude ~±35°. With the sunspot cycle period assumed equal to 11.2 yr, the average speed of the meridional circulation is found equal to ~3 m/sec.

The recent progress in development of observation technology has made possible to make more and more precise measurements of meridional flows on the Sun. With an HMI (Helioseismic and Magnetic Imager) onboard the Solar Dynamics Observatory (SDO) satellite launched in February, 2010, it was possible to detect meridional flows orientated towards the poles on the solar surface. The results are obtained with cross correlation analysis of a family of magnetic elements on high-quality magnetograms [Rightmire-Upton et al., 2012]. The curve of relationship between the latitude and the speed of meridional flow resembles a sinewave graph (an antisymmetric curve relative to the equator), with the maximum values ~8−12 m/sec observed at latitudes ~±45° and zero values near the equator and at the poles (the measurements were performed at latitudes up to ±85°).

Investigation of the Sun's deeper layers according to the HMI data was based on helioseismological analysis of the time of passage of acoustic waves propagating in the Sun's interior [Zhao Junwei et al., 2013]. In the shallow layer to the depth of 0.91R (where R is the radius of the Sun), a meridional flow is found running towards the pole at the speed of 15 m/sec, which is consistent with results of Rightmire-Upton et al., [2012]. Beneath this layer, at the depth of (0.82−0.91) R, a meridional flow was found running towards the equator at a speed of ~10 m/sec. Besides, below the depth of 0.82R, another pole-orientated meridional flow was found. An error of helioseismological measurements of the speed is ~1 m/sec on the surface of the photosphere and increases to 10 m/sec below 0.80R. Therefore, analysis is only performed to the depths of 0.75R due to a high noise level (the base of the convective zone is at ~0.7R).

On the whole, the results of the studies on HMI (SDO) are consistent with the meridional circulation flow suggested in this paper (Figure 2), if we assume that the sunspots (sunspot groups) migrate to the equator in the second layer (0.82−0.91) R and then, near the equator, submerge to a layer below 0.82R, where they are enhanced by the dynamo mechanism, and, once they reach the latitude ~±35º, they emerge onto the surface of the photosphere. In the upper shallow layer of meridional circulation system, there occurs migration of spot fragments, quiescent prominences (filaments) and unipolar magnetic regions to the pole which form high-latitude magnetic fields.

3. Magnetic Toroids

Any physically reasonable model of the sunspot cycle should be based on observational datas on solar activity. The model needs to solve the problems of the transfer of magnetic energy from deep layers to the surface of the sun, neutralizing the magnetic buoyancy, low sunspot temperate, etc. For elimination of the aforesaid difficulty of displacement, the global toroidal field extended in the latitudinal direction is replaced with a multitude of small toroidal rings of magnetic force lines (hereinafter referred to as "magnetic toroid", or just "toroid"). A transportable local toroid made of a Ω-like loop (Figure 3) through reconnection at the base of force lines of the toroidal-orientated global field is proposed. At a certain point prior to polarity reversal of the main dipolar field, the tension on the lines of force weakens thereby increasing the probability of Ω-like loop to break away from the parent toroidal field (Figure 3). As a result, a new closed field toroid originates which is consistent with Hale's law and has a relatively weak field: this is the toroid, which acts as a "seed" field for dynamo or "an embryo of solar activity", as it was referred in the figurative terminology by Rubashev [1958].

It should be noted that a simple toroid is unstable owing to heterogeneity of magnetic field along the cross-section. For stability, the lines of force must be wound around the annular axis of the toroid with a certain winding speed characterized by the winding (or helicity) parameter Spitzer [1958] shows that such lines of force are laid in a highly accurate way, onto the toroidal (so-called "magnetic") surfaces and stay on them forming a family of surfaces placed one inside another. Morozov and Solovyov [1963] presented detailed study of structures formed by magnetic lines of force, in particular, to morphology of toroidal magnetic fields. The authors note that a balanced hydrodynamic configuration retained by the magnetic field may only be obtained in a toroidal system. Toroidal fields made up of magnetic surfaces placed one inside another are better protected from environmental effects. In the authors' wording, the toroidal fields occupy a certain toroidal volume confined with a "separatrix" being a surface of separation of the inner part of toroidal field from the outer part. Within the separatrix, the lines of force are not split and make a virtually unlimited number of revolutions around the larger circumference of the torus. If the separatrix is deformed (generally, in the form of slits), an exchange takes place between the inner and outer regions of the toroidal field.

The helicity of the magnetic line of force in the toroid may be considered as a result of running of force-free current along the annular axis, where, for the stability conditions to be met, the force-free current must be limited depending on a specified value of annular magnetic field i.e., Kruskal-Shafranov condition. Such annular current creates a magnetic moment orientated normally to the plane of the toroid and acts as a source of a dipole magnetic field.

Therefore, a multitude of toroids with the same orientation of annular current creates an aggregate poloidal magnetic field, and the above mechanism is alternative (or additional) to the known □-effect for self-sustaining sunspot cycle. The appearance of a post-flare loops spread out like a fan and "strung" on threads connecting the same, demonstrates the reality of lines of force of dipole magnetic field penetrating the toroids. One could also suppose that the tension of the lines of force of the dipole field prevents the toroids from floating completely off the photosphere .On rising into the surface of the Sun, a vertically orientated toroid forms a bipolar group at the areas of its intersections with the surface of the photosphere in the form of two spots of the opposite polarity (figure 4). In the submerged state, a toroid is (to the first approximation) a closed object isolated from the environment with a strong magnetic field. Therefore, the process of surfacing and submergence depends only on the weight difference of the toroid and the surrounding matter displaced thereby. If the toroid's weight is smaller than that of the displaced matter, the toroid would float up; if its weight is larger, it would submerge. A toroid is in the state of hydrostatic equilibrium in the environment, where the stronger its magnetic field, the more buoyant the toroid is, as the pressure of the matter of the toroid is supplemented with the magnetic field

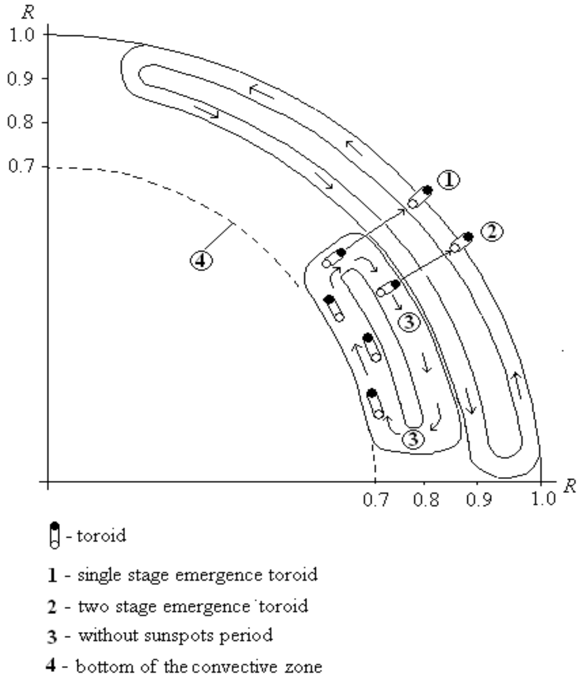


Figure 2. An 11year Sunpot Cycle model

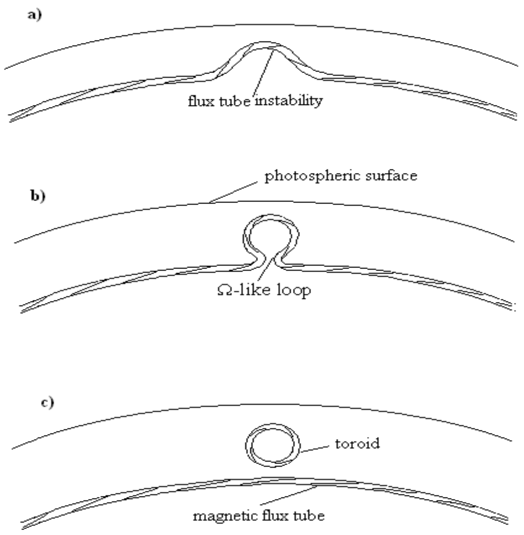


Figure 3. Formation of toroid

pressure. Toroids are moved by meridional circulation along with the flow of matter, where slippage is allowed (the annular field is only freezed into the matter of the toroid's inner volume). Emergence of toroids becomes easier and faster, as the circulation flow and the magnetic buoyancy act synergistically. The submergence process, on the contrary, is somewhat slowed down due to magnetic buoyancy, yet by the time of submergence near the equator the fields of active areas are weakened and, hence, become less buoyant.

An important clarification should be made, which is related to observance of equality of temperatures inside and outside the magnetic tube of force. Buoyancy arises, as the gas pressure inside the tube is smaller than the pressure outside the tube by the value of magnetic pressure. If a temperature difference occurs for some reason or another, the toroid's ability to isolate the inner matter from the outer environment enables to retain this temperature difference. One should also keep in mind that the ambient temperature is increased very fast, whereas the energy exchange between the environment and the inner volume of the toroid is considerably limited. Here, a low matter temperature in the toroid would lead to higher density and lower (or even completely neutralized) magnetic buoyancy. As an example of such low- temperature objects,

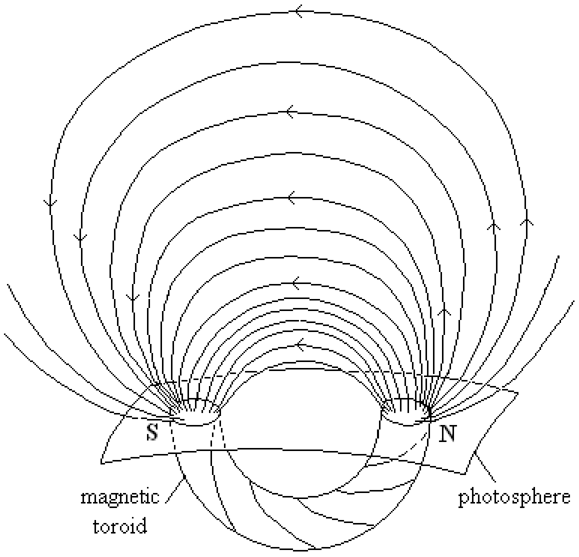


Figure 4. Bipolar Sunspot Group

one could cite umbra of sunspots with a temperature (~4500º K) against the background of the surrounding photosphere (~6000º K).

In the state of partial emergence, a toroid forms two spots of different polarity, each consisting of a cold umbra and a surrounding penumbra with a temperature intermediate between that of the photosphere and the umbra. A toroid partially emerging above the photosphere can no longer be considered a closed system, energy being lost through the ends (spots) of the submerged part. As a result, the submerged part is cooled down and becomes denser, which results in lower buoyancy. The penumbra, which is ~500 km deep and is formed of magnetic lines of force spread like a fan (according to Parker), has the density of the chromosphere and acts as a “float” creating a reserve of buoyancy for the submerged part. The Evershed effect is probably related to formation of slits under the penumbra on the separatrix, which results in outflow of a certain volume of matter out of the spot in the radial direction.

4. Sunspot Cycle Model

In this article a schematic, logically straightforward model of sunspot cycle is described. It is started with movement of primordial toroids and old decaying active regions from 35 º latitude by the meridional circulation flow towards the equator to the latitude ~±5º, where they are submerged into the Sun’s interior, with retaining their vertical orientation (Figure 2). As toroid and old active regions are submerging, they are being compressed by external pressure and brought to a more or less compact state. Once they reach a certain depth at the base of the convective zone, below the zone of formation of supergranules [Parker, 1979], the toroids gradually rotate by 90°, according to the flow of matter and migrate for reduction of hydrodynamic drag in the horizontal position in parallel to the base of the convective zone. At this section, there occurs efficient enhancement of the magnetic field of embryon and decaying active region fragments by the dynamo mechanism up to ~100 kGs [Spruit, 2010]. Prior to surfacing, the toroids once again rotate by 90° according to the flow of matter, while assuming a vertical orientation. On the aggregate, there occurs a 180° rotation of the toroid plane (the top and the bottom of the toroid change their places; therefore, the polarity of the spots is reversed), which automatically ensures observance of Hale’s law in the new cycle for bipolar groups formed by the toroids. Toroids with a field enhanced by the dynamo mechanism emerge at the latitude ~±35º (Figure 2-1), where a decrease in external hydrostatic pressure results in an increase of the toroid volume. If its smaller diameter becomes 5 times larger (the cross-section area is increased 25-fold), the magnetic field of the spot on the Sun's surface goes down to the observable value of ~4 kGs.

More than a half of sunspot groups are known to have a lifetime shorter than two days (for the longest-lived groups 100 days) [Bray and Loughhead, 1965], and so during this time they are able to move only a very short distance from the place of surfacing. Such short lifetimes may be explained by a small reserve of buoyancy of sunspot groups. This flow pattern suggests migration of a considerable part of sunspot groups (toroids) towards the equator in the submerged state (Figure 2-2) in the second layer of meridional circulation (0.82−0.91) *R.* As was considered in section 3, toroids allow a decrease (up to complete neutralization) of magnetic buoyancy; that is why the idea of intermediate floating of toroids up to the second circulation layer is quite justified. From this layer, toroids randomly emerge onto the surface, with the condition of appearance of sunspots on the photosphere met. What is materialized is a two-staged emergence of toroids (Figure 2-2), which means creation of observable distribution of sunspot groups by latitude (Maunder "butterflies"). Existence of a threshold for surfacing of spots was suggested in [Leighton, 1969] with introduction of a critical field value ~1.5 kGs. As was shown in the previous section, the aperture of the toroid is penetrated by the self-poloidal field, and the tension of force lines such fields probably prevents free emergence of spots with a field value lower than the threshold.

It should be noted that migration of toroids occurs in the layer of (0.82−0.91) *R*, in which dynamo enhancement of magnetic field is implemented in the Babcock-Leighton model, and the random emergence of toroids may be caused by additional enhancement of their field to the critical value. Toroids with fields of a smaller value do not emerge to the surface and move to the equator remaining in the submerged state. One should also take into account that some of the groups may remain submerged up till the following cycle. In the submerged state, the toroid is mostly located in the second circulation layer and is moving toward the equator at the speed of flow. When floating to the surface of the photosphere, the toroid will experience some impeding action from the first layer, though this effect will not be very noticeable, given the short lifetime of the spots.

The preceding (*p*-) and the following (*f*-) spots of bipolar groups with fields of 1.5÷4 kGs emerge to the surface of the photosphere at the latitude of ~±35°, according to Maunder "butterflies" and migrate, while developing intensely, towards the equator. As is established from observations, the rise to the peak of activity occurs faster than the decline. The peak of activity corresponds to presence of the maximum number of active regions (sunspots and sunspot groups) on the photosphere. Accumulation of toroids in the second layer of equator-ward meridional circulation and their further emergence (in a random way) to the surface are the result in the fast rise of the peak of activity. As the sunspots migrate towards the equator, they participate in active processes involving release of magnetic energy, which leads to decay of sunspot groups, where the *f*-spot is less stable and disintegrates faster than the *p*-spot. As follows from observations, fragments of the *f*-spot diffuse towards the pole (in the upper layer of meridional circulation), while the *p*- and *f*-spots keep moving to the equator. However, at the same time, fragments of the *f*-spot must be kept associated with the *p*-spot, and the tensions of lines of force between them impede the speed of movement of the *p*- spot (and the entire group, as a whole) to the equator. All this results in a post-peak decline of activity, which is slower compared to the fast rise. Besides, the slowdown of the *p*-spot decreases the initial tilt of the bipolar group axis to the latitudinal direction. At the time of a change of a sunspot cycle, a period (Figure 2-3) is observed, when there are no spots on the Sun's surface. This is also related to the slowdown effect resulting in accumulation of toroids in an area and origination of a spotless area on the meridional circulation trajectory. The characteristic view of Maunder "butterflies" is explained by this mechanism, as well. The upper (frontal) outline of the wings (Figure 1b) makes a larger angle with the axis of symmetry matching the equator (the derivative and the speed of movement are larger), while the lower (rear) outline of the wings forms a more acute angle with the axis (the speed is lower). From Maunder "butterflies" one may roughly estimate that the speed of migration of the spots prior to the peak is ~3 times as high as the speed by the end of the cycle.

In spite of the speed fluctuations along the trajectory, the meridional circulation movement is assumed to be stationary, meeting flow continuity condition. An estimate of the circuit-average matter movement speed for a cycle period 11.2 years gives a value of ~3 m/sec (in section 2). The maximum speed of meridional circulation in the second layer found by Zhao Junwei et al., [2013] is ~10 m/sec. unfortunately, the value of circulation speed near the base of the convective zone is not known precisely, but we may assume that it is ≤3 m/sec. Given the counter meridional circulation at the equator, on the section of submergence from the surface to the base of the convective zone, the speed of migration of toroids must be even lower. In calculation of the average circulation period, the largest contribution is made by the circuit sections with the lowest circulation speed; one can state quite satisfactory accordance between the estimated and actual periods of a sunspot cycle.

While the active regions (sunspots and sunspot groups) are moving towards the equator, the fragments of active regions, along with unipolar magnetic regions and quiescent filaments (prominences) are migrating towards the pole in the first layer of meridional circulation R>0.91. The main distinctive feature of objects involved in these movements is the value of magnetic fields related thereto: ≥1.5 kGs for the first objects and ~100−200 Gs for the second objects (except for unipolar magnetic formations characterized by longer lifetimes and stronger fields). The two-circuit meridional circulation enables to distribute them apart to different depths. The first objects in the form of sunspots with the strongest magnetic fields on the surface of the Sun are moving towards the equator occupying the layer of (0.82−0.91) R. The second objects are migrating in the upper layer of poleward meridional circulation of R>0.91, mostly in the photosphere's convective granulation zone (the magnetic energy of these objects being comparable to kinetic energy of convective granulation).

5. Accordance of the Model with Observational Data

Next, the matter of accordance of the model with observed sunspot cycle properties is considered. As follows from observations, the *p*-spot is more compact and has a longer lifetime, compared to the *f*-spot. Babcock [1961] suggested that compactness of the *p*-spot is explained by more vertical orientation of lines of force of the field. Leighton [1969] presented a view that lines of force of the *p*-spot are wound stronger than those of the *f*-spot, and are therefore more resistant to being "sliced away" by supergranulation currents. It should be added to the above suggestions that in the proposed model with toroids, the *p*-spot remains to be the preceding one throughout their lifetimes; what is changed is just the polarity of magnetic fields in cycles. And all the properties, such as the compactness and more vertical orientation of the field, are retained with the *p*-spot and are transferred from cycle to cycle.

At the moment of emergence of active regions at the latitude ~±35°, the bipolar group axis connecting the centers of the *p*-spots and the *f*-spots is orientated at an angle ~10° to the latitudinal direction, this tilt angle gradually decreasing along with movement towards the equator. Leighton, [1969], explained the tilt of the line of centers of the active region by a cyclonic effect, but with no description of a specific mechanism of origination of the inclination. The *p*-spot is more compact than the *f*-one; therefore, it emerges faster and slightly ahead of the *f*-spot. Such movement may be interpreted as rotational relative to the geometric center of the emerging toroid, which leads to origination (in case of a small initial inclination) in the horizontal plane of a torque made up of a pair of Coriolis forces applied to the spots. As a result, during emergence of the bipolar group, there occurs a rotation (by ~10°) of its axis from the latitudinal direction. With further advancement to the equator, the tilt angle of the sunspot group is getting smaller due to a slowdown of movement of the *p*-spot, as was described above in section 3.

Repeated appearance of active regions at the same places in the old and new cycles was noted in the paper of Bumba et al.,[1968] and can hardly be explained within the generally accepted models. In the toroidal model, these are remains of the previous cycle active regions, which are used as a seed for dynamo, and in the new cycle, “memory” is kept of the old cycle, which determines repeatability of location of active regions. The most powerful argument in favor of reality of toroids is presented by observations of loop prominences (prominences of sunspots) near the limb with broadband filters (8 Å) centered, at the H-alpha line. The loops generally have a shape of an oval extended upwards rather than a circular shape, but this is due to the projection effect, as at limb observations the scale along the line of sight is decreased. The bases of loops are supported by umbrae of sunspots, where each loop is supported by its own umbra (or a large pore). The cross-section of loops varies insignificantly with variation of altitude, which may be explained by availability of longitudinal electric current along the loop. For a current to arise, there must exist a variable magnetic flux covered by this current. At first glance, such flux has nowhere to come from. In a high quality image of loop prominences obtained by Bumba and Kleczek [1961] it can be clearly seen that individual loops are mutually wound (intertwined) between themselves in two or three turns in a so-called magnetic bundle. And if there occurs a variation of magnetic flux in a loop, a current will arise in the adjacent loop owing to mutual intertwining of lines of force. Given large values of fields in sunspots (pores), one can expect very high currents in the loops. It is generally thought that the matter of prominence is condensed from its coronal environment, though this brings about a hard-to-solve problem of deficit of masses. If we consider, in addition to the electron constituent of the current, its proton constituent (which is 43 times smaller), such proton current may act as an agent for delivery of matter to the upper part of the loop. Neutral hydrogen forming as result of recombination would flow freely down along the surface of the both branches of the loop.

Another argument to support existence of toroids is presented by post-flare loops, whose appearance on the surface of the Sun may be explained by the fact that a flare triggers emergence of a family of toroids being submerged in the second layer of meridional circulation.

6. Conclusion

Based on the resent helioseismic observation, an 11-year sunspot activity cycle is suggested, where magnetic toroids with closed annular magnetic field are used for magnetic energy transfer. Meridional circulation flow transports toroids with magnetic fields enhanced by the dynamo mechanism from the layer near the bottom of the convective zone 0.82>R>0.7 into the layer of 0.91>R>0.82. From this layer, toroids randomly emerge up to the layer of R>0.91, where the magnetic energy brought from the interior is spent on various manifestations of solar activity. The toroid efficiently isolates the inner matter from the environment, and this property enables to eliminate excessive magnetic buoyancy. This is achieved by maintaining a lower temperature and a higher density in the inner volume of the toroid, compared to the environment. The sunspot cycle period is mostly determined by the speed of meridional circulation. A bipolar group is formed at the place of intersection of the magnetic toroid with the surface of the photosphere. Observance of Hale's law is achieved automatically by a 180º rotation of the toroid plan at each cycle of meridional circulation movement. The main dipolar (poloidal) magnetic field required for self-sustaining activity cycle is created as a sum of dipole magnetic fields from force-free currents running along the annular axis of toroids. Decay fragments of sunspots, unipolar magnetic regions and quiescent filaments (prominences) are moved towards the pole by shallow meridional circulation in the layer of R>0.91. Proposed sunspot cycle model is in good agreement with numerous properties and characteristics of solar activity. Observable manifestations of magnetic toroids are loop prominences and post-flare loops.

In future, it would be desirable to increase the precision of helioseismological measurements, though the long series of observations at the currently obtained precision level may be a decisive argument in favor of correctness of a sunspot cycle model.

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