J. Astrophys. Astr. (2000) **21,** 365–371

Mechanism of Cyclically Polarity Reversing Solar Magnetic Cycle as a Cosmic Dynamo

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Abstract. We briefly describe historical development of the concept of solar dynamo mechanism that generates electric current and magnetic field by plasma flows inside the solar convection zone. The dynamo is the driver of the cyclically polarity reversing solar magnetic cycle. The reversal process can easily and visually be understood in terms of magnetic field line stretching and twisting and folding in three-dimensional space by plasma flows of differential rotation and global convection under influence of Coriolis force. This process gives rise to formation of a series of huge magnetic flux tubes that propagate along iso-rotation surfaces inside the convection zone. Each of these flux tubes produces one solar cycle. We discuss general characteristics of any plasma flows that can generate magnetic field and reverse the polarity of the magnetic field in a rotating body in the Universe. We also mention a list of problems which are currently being disputed concerning the solar dynamo mechanism together with observational evidences that are to be constraints as well as verifications of any solar cycle dynamo theories of short and long term behaviors of the Sun, particularly time variations of its magnetic field, plasma flows, and luminosity.

Key words. Dynamo—solar cycle—polarity reversal—differential rotation—turbulence—global convection.

1. Solar dynamo and cyclically polarity reversal process in terms of magnetic field line stretching and twisting and folding inside the convection zone of the sun

The basic process of the solar cycle can easily and visually be understood without the help of a computer in terms of magnetic field line stretching and twisting and folding process by a flow of differential rotation and a non-axisymmetric flow such as global convection inside the solar convection zone in three-dimensional space (Yoshimura 1972, 1983, 1993).

It is well known that the magnetic field line stretching by the plasma flow of differential rotation, observed at the surface of the Sun as the equatorial acceleration, can explain the following part of the Hale's polarity rules of the solar cycle.

- The magnetic axis of a bipolar sunspot group of the Sun is almost always parallel to the equator.

- The polarity relation of preceding and following sunspots of the bipolar sunspot group is almost always the same for each northern or southern hemisphere during one solar cycle.
- This polarity relation of one hemisphere is opposite to that of the other hemisphere (Babcock 1961).

However, there was some confusion in this model about the mechanism of the polarity reversal part of the Hale's polarity rules and about the mechanism of how the latitudes of appearance of the sunspot groups migrate from mid-latitudes toward the equator as the solar cycle progresses.

This reversal process also can be understood in terms of magnetic field line deformation by plasma flows in the same way as the magnetic field line stretching by the flow of differential rotation. All we need for this process is an additional non-axisymmetric flow twisted by Coriolis force with spatial scale of the order of the diameter of the Sun. An example of such a flow is a convection which flows upward first and then horizontally and later downward to return horizontally to the upflow motion. This makes one cell of the flow system. The helicity vector of the twist is horizontal in the direction of the rotation, contrary to the case of many turbulent dynamo models whose helicity vector is generally vertical.

The first step in the understanding of the process is the deformation of the magnetic field lines by upward and downward motion of a non-axisymmetric flow. Suppose, first of all, that there are horizontal magnetic field lines stretched in the direction of rotation by the flow of differential rotation. The magnetic field lines are raised (pushed down) by upflow (downflow) motion of the non-axisymmetric flow.

The second step is the twisting of the magnetic field lines deformed by the process of the first step. The twisting is due to the fact that the horizontal motion of the non-axisymmetric flow is deflected to the right (left) in the northern (southern) hemisphere by Coriolis force. The horizontal flow in the same (opposite) direction as (to) the rotation is deflected toward the equator (poles) in both hemispheres. As a result of this process, a horizontal helical structure is formed in the streamlines of the flow. The direction of the twist of the helical structure, or the helicity vector of the structure, is horizontal and is in the same (opposite) direction as (to) the rotation in the upper (lower) part of the cell in the northern hemisphere. In the southern hemisphere, the direction of the twist is opposite to the case of the northern hemisphere. The magnetic field lines are twisted by the flow so that the field lines become almost parallel to the streamlines of the flow.

The third step is stretching of the deformed and twisted magnetic field lines by the flow of differential rotation. If the equator is rotating faster than the poles as in the case of the Sun, for example, the flow of differential rotation acts on the twisted magnetic field lines in the following way. The horizontal portions of the magnetic field lines, which are deflected by the twisted non-axisymmetric flow toward the equator, are carried in the direction of rotation at a rate faster than that of the portions deflected toward the poles in both hemispheres. In a reference frame rotating with the mean speed of the differential rotation, the portions deflected toward the equator look like being stretched in the same direction as the rotation while the portions deflected toward the poles look like being stretched in the opposite direction to the rotation. As a result of this process, the flow of equatorial acceleration of this step acts on the magnetic field lines in the following two different ways for the upper and lower parts

of the flow cell. In the upper part, the magnetic field lines near the surface in the horizontal portions of the flow cell moving in the same (opposite) direction as (to) the rotation are deflected toward the equator (poles) and are stretched toward the same (opposite) direction as (to) the direction of the rotation. In the lower part, the magnetic field lines near the bottom behave in the same way as the field lines of the upper part near the surface.

The fourth step is the polarity reversal of the magnetic field and formation of a reversed magnetic field line system. When the processes in the three steps described above continue, the magnetic field lines near the surface (bottom) in the upper (lower) part of the flow cell, deflected both toward the equator and the poles, keep being stretched toward the same direction as the rotation and the field is strengthened. On the other hand, the magnetic field lines away from the surface (bottom) in the upper (lower) part of the cell, deflected both toward the equator and the poles, are folded to reverse their direction. One reversed magnetic field line system is formed and replaces the original magnetic field line system in the layer away from the surface (bottom) in the upper (lower) part of the cell. Since the whole process take place sequentially and continuously, a cyclically polarity reversing magnetic field line system is formed in the upper (lower) part of the cell which propagates toward the surface (bottom).

The equatorial acceleration, which we assumed in the above example, is not a special form of the differential rotation. The differential rotation can take any form which is determined by dynamics of the convection zone. In any case of the form of the differential rotation, a cyclically polarity reversing magnetic field line system is formed and the direction of propagation of the field line system is perpendicular to the gradient of the differential rotation. In other words, the waves propagate along iso-rotation surfaces. In the upper (lower) part of the cell, the propagation is toward the left-hand (right-hand) direction with respect to the gradient vector of the differential rotation in the meridional plane in the northern hemisphere. In the southern hemisphere, the direction of propagation is opposite to the case of the northern hemisphere.

Since stretching of a magnetic field line gives rise to strengthening of its magnetic field and hence production of a magnetic field energy, this process is a dynamo mechanism. The wave is called a dynamo wave. When one magnetic field line system of the dynamo wave appears on the surface of the Sun, one solar cycle activity occurs. The butterfly diagram of the solar cycle reflects a cross section of the field line system of the dynamo wave at the surface of the Sun. The wave propagates along iso-rotation surfaces inside the Sun and obliquely encounters the surface of the Sun.

The requirements for the non-axisymmetric flow that can act as a dynamo together with the flow of differential rotation of the Sun by the processes described above are the followings.

- The whole pattern of the non-axisymmetric flow cell must propagate around the rotational axis of the Sun. Then in the reference frame that is rotating with the speed of the propagation, the flow of rotation looks like a zonal flow passing through the propagating cell. Only in this case, the magnetic field lines are not wound up and are not entangled around the cell. Global convection and Rossby. waves in a rotating system have such characteristics due to the influence of Coriolis force.
- Speed of the flow and the influence of Coriolis force on the flow which makes the flow pattern twist and propagate to drive the dynamo must be strong enough to

withstand the diffusive action of smaller scale flows. Diffusive smaller scale flows are defined as those flows that cannot feel the influence of Coriolis force strongly enough to act as a dynamo and disperse the magnetic field energy.

2. Historical review of formulation of solar cycle dynamo as a generation and polarity-reversing mechanism of the magnetic field of the sun

In order to understand the meaning of the solar cycle in a broader context of science and technology, we briefly review in the following a history of the concept of a cosmic dynamo.

When understanding of the nature of electricity and magnetism was in its infancy, Siemens invented a self-excited dynamo in laboratory (see Krause 1993). A dynamo is a machine that generates electric current and associated magnetic field. It was discovered by Faraday that electric current is generated in electrically conducting wires when the wires move across magnetic field lines created by a permanent magnet or by electric current flowing in an independent set of wires. A self-excited dynamo is a dynamo without a permanent magnet or a battery that generates electric current. Siemens demonstrated that such a machine is possible with two sets of wires that rotate with respect to each other. The first set of wires was set on a table of laboratory. The second set of wires rotated inside the first set of wires. However, generation of electric current and associated magnetic field of this machine was unstable in the sense that generation did not always occur.

The two sets of wires of the Siemens' self-excited dynamo were embedded in the magnetic field of the Earth. When the second set of wires rotated, it moved across the magnetic field lines of the Earth to generate a seed current that was feeded to the first set of wires. This seed current, flowing in the first set of wires, gave rise to a magnetic field. The rotating second set of wires moved across the field lines of this magnetic field to generate electric current in the second set of wires which was feeded to the first set of wires. This process continued to amplify the current and the associated magnetic field. Thus generation of the current and magnetic field was sensitive to the direction of the second set of wires with respect to the magnetic field lines of the Earth. Whether or not the seed current was strong enough to start the whole process depended on the direction of the second set of wires with respect to the magnetic field lines of the Earth.

The present day industrial dynamo originated by Siemens' invention uses a smaller secondary dynamo with a permanent magnet or a magnet produced by a small amount of electric current to feed the seed current of the Siemens' self-excited dynamo.

The basic question of a cosmic dynamo driven by plasma flows is closely related to the situation of the Siemens' dynamo. It also requires a seed current and field. The dynamo does not generate a magnetic field out of nothing. It amplifies an infinitesimal seed field to a field of finite amplitude. The infinitesimal seed field is present in any plasma where particles with electric charges are always present in micro space to move around and produce magnetic field. When this magnetic field in micro space is averaged over some macro space, it is difficult to completely cancel out the magnetic field. Some infinitesimal field is always present even in macro space. The question of a cosmic dynamo is whether or not there is any plasma flow that can amplify this infinitesimal field to a field of finite level without wires and rods that

guide electric current and without permanent magnets and batteries. The question is essentially linear with respect to the magnetic field in the sense that the Lorentz force of the produced magnetic field acting on the flow does not come into this basic question. Only when we ask about the level and magnitude of the generated electric current and magnetic field or the amplitude of the solar cycle, we need to consider the nonlinear action of the Lorentz force on the dynamo driving flows and mechanical motions. When we investigate the long-term behavior of the solar cycle, this nonlinear aspect of the problem becomes essential.

We here return to the era when understanding of the nature of electricity and magnetism was still in its infancy. When Maxwell formulated the basic equation governing electricity and magnetism, he proposed that any rotating body with electric charges should be accompanied by a magnetic field. This rotation of electric charges is equivalent to a motion of electric charges and hence is equivalent to electric current. After Rowland proved this claim, Schuster pushed this proposition further that any rotating body which is electrically neutral should possess a magnetic field. Maxwell and Schuster conjectured that rotation and magnetic field should be related with each other in a fundamental way as a part of nature of space and time.

This proposition or conjecture prompted Hale in 1908 to test the idea for the case of sunspots. The H_α features around sunspots observed by Hale showed a pattern that was similar to that of a vortex motion of plasma. Hale thought that this must be equivalent to rotation and hence sunspots should have a magnetic field. By applying the Zeeman effect to the spectrum of light emitted from sunspots, he discovered magnetic field of sunspots. Although Hale's conjecture that the H_α features around sunspots represent vortex and rotational motions was wrong, this was the first suggestion that plasma motions without wires and rods could generate a magnetic field. This is the birth of concept of a cosmic dynamo. Since Larmor included this mechanism in his paper in 1919 as one of possible mechanisms of generation of magnetic field in cosmos, Larmor is often erroneously cited as the first person who suggested dynamo mechanism for generation of magnetic field in cosmos by plasma flows. He visited Mt. Wilson Observatory.

This concept of generation of magnetic field by vortex or rotational or axisymmetric plasma flows alone was proved to be unable to amplify and maintain magnetic field by Cowling in 1933–1934. This theorem, called Cowling's anti-dynamo theorem, was a great challenge to the concept of a cosmic dynamo driven by plasma flows.

A more fundamental meaning of the rotation-magnetic field relation was implied by Einstein's general relativity. In his paper of general relativity, he started his discussion of general relativity by Mach's Gedanken (thought) experiment where two bodies are rotating with respect to each other in an empty space. Since a person standing on each body can measure that one body is a perfect sphere and the other is an ellipsoid, for example, it can be concluded that the body with the ellipsoidal figure is rotating and hence centrifugal force is acting on the body. However, according to the principle of general relativity, both bodies should be equivalent. Why should one body have an ellipsoidal figure? Einstein's answer was that the nature of space and time of the two bodies are determined by distribution of mass at a far distance. This means that there could be no pure empty space. Even when we do not discuss the problem of contradiction of the concept of existence of ether by the name of structure of space and time as an absolute reference frame and the concept of general relativity which denies

the existence of any absolute reference frame, we see in this answer of Einstein a limitation of the 20th century physics. Although Einstein's general relativity theory discussed only the aspect of equivalence of gravity and acceleration, the Mach's Gedanken (thought) experiment and Einstein's answer implied that existence of magnetic field of a rotating body is determined by mass distribution at far distance. As we have seen in the previous section, the solar dynamo works only under the influence of Coriolis force. This means that existence of a cyclically polarity reversing magnetic field depends on the mass distribution at a far distance according to the Einstein's thinking. Can existence of magnetic field in a local space be related to existence of mass distribution at a far distance?

To add a few words to this fundamental question, it was discovered by Barnett in 1914, at around the times of Einstein's general relativity which was published in 1916, that when a ferromagnetic material was rotated rapidly, it was magnetized around the rotational axis. Conversely, it was found by Einstein and de Haas in 1915 that when a ferromagnetic material was magnetized, it began to rotate around an axis. These two findings led many scientists to believe that there must be a fundamental relation between rotation and magnetic field.

On the other hand, facing the Cowling's challenge against the concept of a cosmic dynamo that the plasma motions could not generate magnetic field and could not drive electric current in cosmos, Elsassar, a friend of Einstein, proposed that non-axisymmetric flows could work as a dynamo even if axisymmetric flows alone could not work as a dynamo.

Several candidates of these flows have been studied. One class of flows is turbulence. The other class is laminar flows.

In order to avoid confusion, we should state here that there are two classes or concepts of turbulent dynamos. One class of dynamos generates magnetic field locally in a space on the order of the size of the turbulence itself. In this class, the presence of rotation as a whole is not important. It is similar to the case of plasma in micro space in general where charged particles move around to produce electric current and magnetic field. If there are no counteracting smaller scale turbulence that disperse the generated magnetic field, the field can be maintained in principle. In this class of turbulent dynamos, there need not necessarily be a net amount of magnetic field once averaged over some macro space. The other class of turbulent dynamos is under influence of rotation as a whole. In this class, the net amount of magnetic field is expected to exist even when the field is averaged over some macro space and the rotation-magnetic field relation is expected to exist.

In the initial phase of development of dynamo theories, however, the concept of magnetohydrodynamics was hot fully understood. Although existence of the two candidates of dynamo driving flows of global convection and Rossby waves was already theoretically known as the two possible types of oscillatory flow in a rotating spherical system by Margules and Hough in the late 19th century, its relevance to the dynamo problem was not noticed for a long time.

3. Solar cycle

For solar physics, the question is whether or not the global convection exists in the convection zone. If it exists, together with the action of the differential rotation flow,

it cannot avoid driving the solar cycle under influence of Coriolis force of rotation to make its flow pattern twist and propagate.

One of the disputes which are related to the present solar cycle model is the structure of the differential rotation. The fact that the dynamo wave propagates along iso-rotation surfaces was first found by a numerical simulation experiment and was later proved analytically (Yoshimura 1975a, b). The theorem can now be seen and proved visually in terms of magnetic field line behavior without any difficulty and ambiguity. The dynamo wave is a powerful tool for investigation of the structure of the differential rotation. The dynamo model shows that the rotation rate must decrease poleward and increase inward in the layer where the observed sunspot groups originate. We are not sure, however, about the depth where the sunspot groups originate. This structure was often claimed to be inconsistent with the results of the helioseismology. I rather see this difference as another source of information, as well as another observational contraint for further understanding the layer where the sunspot groups originate and for further understanding the vertical stratification of the solar convection zone.

Another source of information concerning the vertical stratification and the related nonlinear long-term behavior of the solar cycle is the solar total irradiance change which I discussed in separate literatures (Yoshimura 1994; 1996; 1997a,b; 1998; and references cited therein).

In conclusion, the cyclically polarity reversing magnetic field is a natural phenolmenon of a cosmic dynamo under influence of Coriolis force of rotation. The solar cycle is a representative example of such a cosmic dynamo.

References

Babcock, H. W. 1961, *Astrophys. J*, **133,** 572.

Krause, F. 1993, in *The Cosmic Dynamo,* IAU Symp. No. 157, (eds.) F. Krause *et al*., (Dordrecht: Kluwer Academic Publishers), 487.

Yoshimura, H. 1972, *Astrophys. J.*, **178,** 863.

Yoshimura, H. 1975a, *Astrophys. J. Suppl*., **29**, 467.

Yoshimura, H. 1975b, *Astrophys. J*., **201,** 740.

Yoshimura, H. 1983, *Astrophys. J. Suppli* **52,** 363.

Yoshimura, H. 1993, in *The Cosmic Dynamo*, IAU Symp. No. 157, (eds.) F. Krause *et al*., (Dordrecht: Kluwer Academic Publishers), 463.

Yoshimura, H. 1994, *Astron. Nachr*., **315,** 371.

Yoshimura, H. 1996, *Proc. Japan Acad*., **72B,** 197.

Yoshimura, H. 1997a, *Proc. Japan Acad*., **73B,** 115.

Yoshimura, H. 1997b, *Proc. Japan Acad*., **73B,** 120.

Yoshimura, H. 1998, *Solar Phys*., **177,** 329.