ON THE CHARACTERISTICS OF THE BASIC FRAMEWORK OF SOLAR ACTIVE REGIONS AND THE MAGNETOHYDRODYNAMICAL STRUCTURE OF THE CONVECTION ZONE

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Abstract. The characteristics of the basic framework of structure and development of solar active regions are interpreted as good indicators of the magnetohydrodynamical structure of the convection zone, the magnetic field lines of which are twisted and are made wave-like by the action of the very large scale non-axisymmetric convection, called here the global convection. The characteristics discussed in this paper are: (i) the preponderance of preceding spots of bipolar sunspot groups in strength and life time relative to the following spots of the groups, (ii) the tilt of bipolar axes of the sunspot groups to the local parallels of latitude, (iii) the forward inclination of normal axes of sunspots inferred from the east-west asymmetry of the appearance and total area of sunspots, (iv) the faster rotation of sunspots than the averaged fluid rotation, and (v) the association of the characteristics of an active region with the presence of an older active region in its vicinity and with the relative disposition of the two active regions.

1. Introduction

The prominent feature of surface magnetic activities of the Sun is that they take the form of Active Regions (AR's) composed of bipolar sunspot groups and their surroundings (Hale and Nicholson, 1938). Though AR's may become very complex when several bipolar sunspot groups appear at the same region, the formation of an Arch Filament System (AFS) with bipolar magnetic characteristics at the beginning of formation of a new AR shows that the fundamental constituents of AR's are the bipolar sunspot groups (Waldmeier, 1937; Ellison, 1944; Bruzek, 1967, 1968, 1969; Weart and Zirin, 1969; Weart, 1970, 1972; Martres and Soru-Escaut, 1971). This bipolar structure of AR's and AFS's has been interpreted as the manifestation of magnetic flux ropes formed in the solar convection zone appearing on the surface. As the mangetic field fluxes of the sunspots constituting AR's are expected to penetrate deep into the solar convection zone (Deinzer, 1965; Yun, 1970), basic characteristics of the structure and development of AR's should be considered as good indicators of the state of the velocity and magnetic fields of the convection zone deep below the AR's.

Recently very large scale nonaxisymmetric fluid motions, which are of convective nature driven by the radial superadiabatic gradient of the solar convection zone (Simon and Weiss, 1968a, b; Vickers, 1971), have been conceived to explain the Ward's (1965) correlation of proper motions of sunspots and the equatorial acceleration (Busse, 1970; Durney, 1970; Yoshimura and Kato, 1971; Yoshimura, 1972a; Gilman, 1972). Yoshimura (1971) has shown that the structure of the magnetic field associated with

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the convective motions in the convection zone may be responsible also for the clusterings of AR's in several longitudinal regions (complexes of activity), the longitudinal distribution of magnetic fields observed at the surface, and their rotational behavior. Moreover Yoshimura (1972b) has shown that the convective motions give the dynamo action and hence can be the basic driving power of the solar cyclic magnetic activities. We shall call hereafter the very large scale nonaxisymmetric convective fluid motions the global convection because they extend over the sphere of the solar surface and are subject strongly to the geometry of the sphere. Since any model of the solar activities should account for in a unified manner both the global and the local phenomena, it becomes important to investigate whether this convection, which has been shown to be responsible for the global scale phenomena of magnetic activities, can explain the basic characteristics and structure of the phenomena of the scale of an AR.

The aim of this paper is to show how the local properties of solar activities, i.e., the characteristics of the basic framework or AR's, bipolar sunspot groups, and sunspots in general, can be explained and interpreted by the global convection and to point out conversely that it will be possible to study the structure of the global convection by investigating the basic characteristics of AR's, bipolar sunspot groups, and sunspots in general.

2. Observational Data

We shall list up first in the following the characteristics of AR's, bipolar sunspot groups, and sunspots in general which will give us informations about the magnetohydrodynamical structure of the convection zone.

(i) The first clue to the understanding of the structure is the fact that the bipolar axes of sunspot groups are nearly parallel to the lines of latitude. This fact has been interpreted as is showing that the general magnetic field lines in the solar convection zone, hence those below AR's, are nearby parallel to the lines of latitude, i.e. the toroidal general field predominates. The rules governing the polarity of the bipolar sunspot groups during successive cycles lead to the understanding of the behavior of the magnetic field in the solar cycle (Hale, 1913; Hale and Nicholson, 1938; Babcock, 1961; Leighton, 1969). However there is a systematic tilt, though small, in the direction of the axes of the sunspot groups, with respect to the local parallels of latitude. The orientation angle γ between the axis of a sunspot group and the east-west line depends on the latitude θ of the group and the dependence is expressed approximately by $\sin\gamma = \frac{1}{2}\sin\theta$ (Brunner, 1930; Leighton, 1969), the preceding spots being nearer to the equator than the following ones. The angle depends also on the phase of the evolution of the sunspot group. Weart (1970, 1972) observed the orientation angle of AFS's of the initial stage of AR's and found that the AFS's with correct tilt, the preceding parts of which are nearer to the equator than the following ones, live longer to become large AR's, and the AFS's with incorrect tilt tend to vanish sooner without becoming large AR's, and that the angle of the tilt is rather random at the initial stage of the evolution though the tilt of the surviving AFS's or AR's become smaller and normal.

(ii) The second clue is the preponderance of the preceding spots in strength and life time relative to the following spots of the bipolar sunspot groups (Grotrian and Künzel, 1950). Sunspot statistics show that the types βp and αp of the Mt. Wilson classification of sunspot groups occur most frequently, predominating over the types βf and αf, thus manifesting the tendency of preceding spots to outlive their following companions (Hale and Nicholson, 1938). According to Weart (1972) there is a correlation between the tilt of the bipolar axes and the asymmetry of the strength and life time of the bipolar sunspot groups, i.e., the preceding spots of the groups with correct tilt tend to preponderate over the following ones, while the following spots of the groups with incorrect tilt, though these cases are rather rare, tend to preponderate over the preceding ones. That there are two types of sunspots with respect to the evolution and life time has also been observed by Bumba (1963), who found that there are two types of area curves of the post-maximum phase of sunspots and sunspot groups. The first type of a very rapid area decrease includes the greater part of nonrecurrent, short-lived groups with small spots, while the secod type of a slow area decrease includes the majority of recurrent groups.

(iii) The third is the asymmetry of the appearance and total area of sunspots with respect to the western-eastern hemispheres, i.e., the excess in sunspot number and total spot area on the eastern hemisphere. This phenomenon was found by Maunder (1907) and two possibilities of the origin of the phenomenon were proposed by her, i.e., (1) the forward inclination of normal axes of sunspots (Minnaert, 1946), and/or (2) the overlying bright facula (Sawyer and Haurwitz, 1972). Sawyer and Haurwitz (1972) found a correlation between the asymmetry of sunspot area with respect to the central meridian and the asymmetry of activities of preceding and following spots described in (ii), i.e., the usual area excess for spots in the eastern hemisphere is reversed for the relatively rare f spot groups of which the regions of following polarity have strong magnetic field. Though Sawyer and Haurwitz considered that the correlation is an evidence that the overlying bright faculae are the cause of the asymmetry of sunspot area, we shall take the standpoint that the forward inclination of normal axes of sunspots is the cause of the asymmetry, because the phenomena described in (i), (ii), and (iv), and the correlations between them interpreted in a unified manner in this paper naturally explain the forward inclination of normal axes of sunspots hence the asymmetry of sunspots appearance and area, and the correlation found by Sawyer and Haurwitz (1972). The overlying bright facula as the cause of the asymmetry is not a necessary consequence of the presence of the correlation, though it may also cause the asymmetry. Whether faculae screen sunspots or not is an independent atmospheric problem.

(iv) The fourth clue is the phenomenon that the rotational period of sunspots (Newton and Nunn, 1951) is shorter than that of the averaged fluid derived spectroscopically by Howard and Harvey (1970).

(v) The fifth is the association of the proper motion and the preceding-following asymmetry of a sunspot group with the presence of an older AR in its vicinity and with the relative disposition of the two AR's (Martres, 1970). Martres (1970) found that a sunspot group formed in the preceding side of an older AR evolves to the type βf of the Mt. Wilson classification, the following spot of which shows an eastward motion greater than in the case of an isolated group, while a sunspot group in the following side of an older AR evolves to the type βp which is associated with a westward motion of the leading spot greater than in the case of an undisturbed group. The difference between the motions of the groups and those of isolated groups is the same in both cases and equal to about $1\overset{\circ}{.}5$ in three days.

3. Interpretations of the Phenomena

The phenomena listed in Section 2 have been discussed previously in terms of the concepts of twists of magnetic flux ropes and radial stratification of the differential rotation (Alfvén, 1950; Lundqvist, 1951; Dungey, 1958; Babcock, 1961; Leighton, 1969; Foukal, 1972). However, the radial structures of the differential rotation required to explain the different phenomena have contradicted each other. For example, the phenomena of the preponderance of preceding spots and of the forward inclination of normal axes of sunspots were interpreted as the result of the faster rotation of the upper layer (Babcock. 1961), while the phenomenon of the faster rotation of sunspots were interpreted to indicate the faster rotation of the lower layer of the convection zone (Foukal, 1972). Moreover the idea that the tilts of bipolar axes of sunspot groups are the twists of the magnetic flux ropes caused by the stretching and rolling by the differential rotation (Leighton, 1969) is difficult to explain the phenomenon of the appearance of as many incorrectly tilted AFS's as correctly tilted AFS's. The velocity field required to explain the phenomena, however, needs not be that of the differential rotation. What is required is the velocity field the scale of which is much larger than the scale of an individual AR.

This velocity field can be provided by the global convection which has been conceived to explain the global scale solar phenomena. It has been shown that there is not only a possibility that the global convection drives the differential rotation (Busse, 1970; Durney, 1970; Yoshimura and Kato, 1971; Gilman, 1972) and the solar dynamo (Yoshimura, 1972b) but also a possibility that the nonaxisymmetric structure of the magnetic and velocity fields may be responsible for the clusterings of AR's and magnetic fields in longitudes and for the proper motions of sunspots (Yoshimura, 1971; see the references cited therein). Hence it is very natural to consider that the convection must affect the dynamics of the AR's and the sunspots themselves. Though the theoretical treatment of the global convection is yet far from complete, the various properties of the convection and magnetic field associated with it, which have been studied by the techniques available at present, have succeeded to explain the basic properties of the velocity and magnetic fields observed at the surface. Hence in the following we shall use for the velocity and magnetic fields the results of the previous studies, in which the velocity and magnetic fields are treated by a linear theory in the configuration of spherical thin shell and the rotation is taken into account by a perturbation method (Yoshimura and Kato, 1971; Yoshimura, 1971, 1972b).

The phenomena of complexes of activity, i.e., the phenomena that AR's tend to cluster in several longitudinal regions and that the regions rotate rigid-body-like (Švestka, 1968a, b; Dodson and Hedeman, 1968) have been interpreted by Yoshimura (1971) that AR's tend to be formed in the regions where general magnetic field inside the convection zone is transported and compressed most near the surface by the radial flow of the global convection. The longitudinal regions have been regarded to reflect

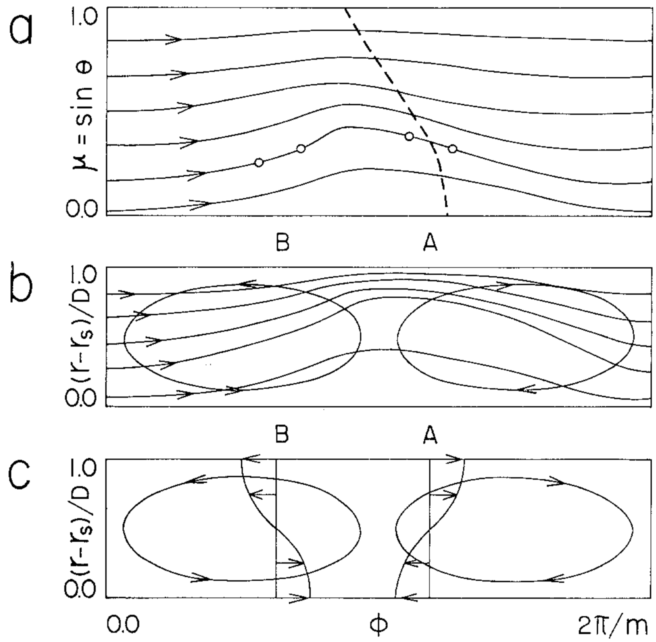

Fig. 1. Conceptual diagrams of the structure of the velocity and magnetic fields in the solar convection zone calculated by a linear theory. Figure a shows the structure of the magnetic field lines near the surface for one wavelength in the longitude ϕ-latitude θ plane. Figure b shows the structure of the magnetic and velocity fields in the longitude ϕ-radius r plane at some representative latitude regions. Figure c shows the radial structure of the velocity field in the ϕ-r plane in the regions where AR's are formed. In the figures, m is a wave-number and a positive integer, r_s is the radius of the inner boundary of the convection zone, and D is the depth of the zone. The field lines in the figures are only conceptual ones which are projected from the field lines in the three dimensional space onto the planes. Hence the density of the lines does not represent the flux of the fields. The regions where the magnetic field is compressed and strengthened most in longitude near the surface by the radial flow of the global convection are localized to several longitudinal regions because of the nonaxisymmetric nature of the convection. The regions are denoted by A and the latitudinal dependence of the regions is shown by the dotted line in the longitude-latitude plane in the case of the dominant mode $P^n{}_n$ of the global convection. Note that the structure of the regions is such that the magnetic field lines in the longitude-latitude plane tilt toward the equator in the same manner as the general tilt of bipolar axes of sunspot groups. The velocity field structure is such that the convection flows in the same direction as the rotation and that the flow is larger near the surface than in the lower regions. Hence the sunspots which appear in the regions rotate faster than the averaged fluid and the radial structure of the velocity field is just what is required by Babcock (1961) to explain the forward inclination of normal axes of sunspots and the asymmetry of magnetic field strength between the preceding and following sunspots (see Figure 5 of Babcock, 1961). Note also that the characteristics of AR's are correlated each other and that, if AR's occur in the regions denoted by B, the situations are reversed to those in A, and the AR's in B show the opposite characteristics.

the pattern of the convection which rotates rigid-body-like if the number of the mode of the convection is small. The phenomenon of the faster rotation of sunspots than the averaged fluid rotation has been interpreted naturally as a result of the phase difference between the patterns of the velocity and magnetic fields of the convection, because the regions where the magnetic field is compressed most near the surface are the regions where the convection flows in the same direction as the rotation due to the phase difference.

This interpretation also explains the preponderance of preceding spots in strength and life time relative to the following spots of the bipolar sunspot groups and the forward inclination of normal axes of sunspots. Because the radial stratification of the velocity field, the scale of which is much larger than that of an AR and which works as a mean field to the phenomena of an AR, of the regions where the magnetic field is compressed most near the surface is such that the velocity component in the same direction as the rotation, composed of the velocity of the rotation itself and that of the global convection, is larger in the upper region than in the lower region even if the radial differential rotation is not present. That is, the local rotational speed is larger at the upper part than at the lower part in the regions where the magnetic field is intensified most near the surface. These circumstances are shown in Figure 1. The structure is just what is required by Babcock (1961) to explain the two phenomena. Hence the two phenomena are related with the phenomenon of the faster rotation of sunspots than the averaged fluid rotation.

In order to explain these phenomena it suffices to think only of the radial-longitudinal structure of the convection zone. For the explanation of the phenomena of the tilt of bipolar axes of sunspot groups to the local parallels of latitude, however, it is necessary to think of the latitudinal-longitudinal structure of the convection zone in the regions where AR's appear. The structure is shown in Figure 1 together with the radial-longitudinal structure. The detailed expressions of the fields in Figure 1 and Figure 2 in the following section are listed in Yoshimura (1971, 1972b). Figure 1a shows the structure of the magnetic field lines near the surface for one wavelength in the longitude ϕ-latitude θ plane. Figure 1b shows the structure of the magnetic and velocity fields in the longitude ϕ-radius r plane at some representative latitude regions where AR's frequently occur. Figure 1c shows the radial structure of the velocity field in the regions where AR's are formed. (The field lines in Figure 1 and in Figure 2 in the following are only conceptual ones projected onto the planes. The lines do not necessarily lie on the two-dimensional planes. Hence the density of the lines does not represent the flux of the fields.) The regions where the magnetic field is compressed and strengthened most near the surface in longitude by the radial flow of the global convection are localized to several longitudinal regions because of the nonaxisymmetric nature of the global convection. The regions are denoted by A and the latitudinal dependence of the regions is shown by the dotted lines in the longitude-latitude plane for one wavelength. The structure of the regions is such that the magnetic field lines in the longitude-latitude plane tilt toward the equator in the same manner as the general tilt of bipolar axes of sunspot groups and that the velocity near the surface is larger than the mean

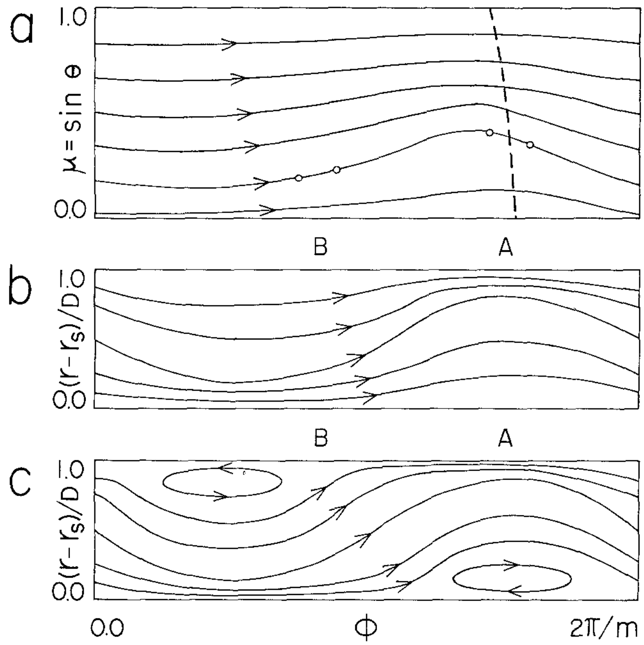

Fig. 2. Conceptual diagrams of the velocity field in the reference frame rotating with the same velocity as the pattern of the global convection which propagates in the opposite direction to the rotation in the reference frame moving with the mean fluid rotation. The rotation of the fluid in the reference frame of this figure appears as a mean flow going in the same direction as the rotation. Figure a is the structure in the longitude-latitude plane. Figures b and c show the structure in the longitude-radius plane in the cases that the magnitude of the velocity of the global convection is smaller (Figure b) or larger (Figure c) than the propagation velocity of the pattern. If the magnitude of the velocity is constant, the system can be considered stationary *only* in this reference frame. Then in this reference frame the magnetic field will approach to a stationary state, the magnetic field lines of which are parallel to the stream lines shown in the figures. Hence the lines in the figures can also be regarded as the magnetic field lines of the stationary state. The actual magnetic field of the convection zone may shift from the state shown in Figure 1 to the state in Figure 2. Note that the latitudinal-longitudinal and the radial-longitudinal structures of the fields in Figure 2 are similar to those in Figure 1 and the features interpreted to explain the basic characteristics of AR's are pronounced more in Figure 2 than in Figure 1. Especially the regions where the magnetic field is compressed and strengthened most near the surface and where AR's are interpreted to be formed and live long preferentially are the regions where the convection flows fastest in the same direction as the rotation near the surface.

rotation and that of the lower zone. The structure can be connected with the structure of AR's if we consider the formation of AR's as the following.

The AR's may be formed anywhere in longitude by the actions of the supergranulation and the magnetic buoyancy in the upper zone where convection of supergranulation prevails if sufficient magnetic field flux is available there. This is inferred by the fact that the magnetic field lines of new AR's or AFS's governed by the action of the supergranulation are tilted rather randomly as Weart's (1970) statistics shows. But as the field lines of the AR's appear on the surface and the AR's grow to become much larger than the supergranules, the magnetic field lines begin to reflect the structure of the field in the deep convection zone from which the magnetic field of the AR's originates. In the regions such as those denoted by *A*, the AR's, reflecting the field lines, show the correct tilt, while in the regions such as those denoted by *B* the incorrect tilt. In the regions *A* the magnetic field flux is supplied from below by the action of the global convection. (This explains the observational fact of appearance of many AR's in one region which has been regarded as difficult to explain in terms of the Babcock's concept of one flux rope in the convection zone (Weart, 1972)). In the longitudinal surface regions other than the regions *A*, however, the magnetic field flux is not supplied from below by the radial flow of the global convection and AFS's and/or AR's formed in the regions cannot help vanishing soon. These circumstances of selection explain the observations of Weart (1970, 1972) and of Bumba (1963) and lead to the result that only the AR's with bipolar axes of correct tilt in the regions *A* tend to live longer and grow, thus the general tendency of correct tilt in the bipolar axes of solar AR's in general appears. At the same time the AR's in the regions *A*, hence AR's in general, rotate faster than the averaged fluid rotation and grow to have the forward inclination of the normal axes of sunspots, and the preceding spots of the AR's tend to outlive their following companions due to the radial structure of the velocity field there.

Rare cases of the longer enduring AR's with incorrect tilt and preponderance of following spots can be understood by the appearance and endurance in the regions *B* by some causes, for example, by fluctuation, or possibly by the appearance of some other modes of the convection beside the dominant mode in the convection zone. The situation of the velocity and magnetic fields in the regions *B* is contrary to the situation in the regions *A*. Hence the characteristics of the AR's in *B* are contrary to those of the AR's in *A*.

This interpretation of the phenomena of the appearance of the types βp and βf of the active regions and of their characteristics in terms of the global convection, i.e., the appearance of the type βp on the forward going flow of the convection and the appearance of the type βf on the background going flow, leads to the explanation of the observation of Martres (1970). In order to show this we must notice the following circumstances. That is, the AR's, once formed on the surface, must move according to the flow of the convection, and as they evolve and age, they must reach to the regions of sink of the convection with the time scale of one month or so if we take the scale of the convection as 3×10^{10} cm and the magnitude of the velocity as 10^4 cm s^{-1}. As the magnetic flux is not supplied there but sucked in beneath the surface instead, the AR's there must grow old and weaken. The background going flow of the global convection lies to the preceding sides of the regions of sink, while to the following side of the regions lies the forward going flow of the convection. Hence an AR formed to the west of an older one which is situated in the regions of sink must evolve to become the type βf which moves to the east according to the flow of the convection, while an AR formed to the east of an older one evolves to become the type βp flowing westward. This is just what was observed by Martres (1970). Though there may be other forces which are also responsible for the proper motions of sunspots, the fact that the difference between the displacements of the sunspots of the above situations and the averaged ones, of about 1°.5 in three days according to Martres (1970), i.e., about 70 m s^{-1}, coincides with the order of magnitude of the velocity of the global convection, strongly supports the idea that the difference of the displacements is due to the global convection.

If we use H_ϕ and H_θ for the longitudinal and latitudinal components of the magnetic fields, the latitudinal dependence of the degree of the tilt γ can be estimated by the value of arctan (H_θ/H_ϕ) at the region where the strength of the magnetic field is maximum in longitude near the surface. This value, though it depends on the state of the mean magnetic field and on the mode of the convection, generally increases from the equator to the middle latitude and then decreases from the middle latitude to the pole for the case of the representative form of the mean magnetic field and the mode of the global convection represented by an associated Legendre function P_n^n which has been regarded both theoretically and observationally to be dominantly excited in the solar convection zone (see Yoshimura, 1972a). Thus the behavior of γ in the sunspot regions explains the Brunner's result of the latitudinal dependence of the tilt of bipolar axes of AR's.

Davies-Jones and Gilman (1970), in their rotating annulus model, calculated the velocity and magnetic fields of the very large scale convection and interpreted the tilt of the bipolar axes of sunspot groups in terms of the fields, but their model requires a rather large value of rotation because the tilt is interpreted as due to the distorsion of the pattern of convection due to the rotation approaching to the limit of heliostrophic flow. Whether the rotation of the Sun is large enough is yet uncertain. In the present model, however, the tilt of the axes of bipolar sunspot groups appears as a result of the phase difference between the longitudinal and latitudinal components of the magnetic field caused by the effect of rotation, and this occurs even if the rotation is small, the phase difference and tilt depending on the magnitude of the rotation. Actually the effect of rotation has been calculated by a perturbation method treating the rotation infinitesimally.

4. Comments on the Velocity and Magnetic Fields of the Global Convection

In the treatment of the velocity and magnetic fields used in this paper, i.e., the treatment of the fields by a linear theory with respect to the amplitudes of the fields, the rotation being taken into account by a perturbation method, there have been some questions. The first is that, as the magnetic field lines would be wound up by the convection as in the case investigated by Weiss (1966), the regular field pattern which explains the phenomena of AR's would not take place when the amplitudes of the fields grow and nonlinear effects become large. If this occurs, however, the regular pattern of Unipolar Magnetic Regions (UMR) would not persist for many years as was observed by Bumba and Howard (1969) and Ambrož *et al.* (1971). The second is that, as the rotation has been regarded to be so small that it can be treated as a perturbation, the phase differences among the fields and their components due to the effect of rotation which explain the characteristics of AR's may not be large enough to make the characteristics conspicuous, especially to make almost all long-enduring sunspots appear in the regions where the convection flows in the same direction as the rotation. There may be spots of less but comparable number on the backward going flow of the convection as well.

In order to answer these questions, we must notice the following circumstances, i.e., the convective pattern is propagating relative to the mean fluid rotation and all physical quantities associated with the convection are proportional to $\sin(m\phi+\sigma_r t+\delta)$, where ϕ is the longitude, m is a positive integer, δ is constant with respect to time and longitude, and σ_r is the frequency of propagation. Theories show that generally $\sigma_r>0$, which means that generally the direction of the propagation is in the east, i.e., in the opposite direction to the rotation, in the reference frame moving with the mean flow (Busse, 1970; Durney, 1970; Yoshimura and Kato, 1971). Hence when the nonlinear effects become large and the amplitude of the velocity approaches to a constant, the system can be regarded as stationary *only* in the reference frame moving with the pattern of the convection. In this reference frame the rotation appears as a mean flow in the direction of the rotation with speed of $(\sigma_r/m)+f(\theta)$, where $f(\theta)$ is the form of the differential rotation in the reference frame to which the value of σ_r refers. Then the stationary pattern of the flow composed of the velocity field of the mean flow and that of the global convection is like wave-like stream lines as those of magnetic field lines shown in Figure 1. Figure 2 shows the stream lines of the velocity field. Figure 2a is the structure of the velocity field in the longitude-latitude plane. Figures 2b and 2c show the structure in the longitude-radius plane in the cases that the magnitude of the velocity of the global convection is smaller (Figure 2b) or larger (Figure 2c) than the magnitude of the mean flow in the reference frame moving with the pattern of the convection.

The state of the magnetic field in the reference frame moving with the pattern may approach to a stationary state in which the magnetic field lines are parallel to the stream lines of the velocity field. Hence the lines in Figure 2 can also be regarded as the magnetic field lines of the stationary state. In this state, the longitudinal regions of the maximum magnetic field strength are the regions where the convection flows fastest in the direction of the rotation at the surface. Thus by considering that the state of the magnetic field shifts from that calculated by a linear theory to that of the stationary state as the amplitudes of the fields become large, the two problems described above can be solved, i.e., the magnetic field lines need not be wound up and almost all long-enduring sunspots appear in the regions where the convection flows fastest in the direction of the rotation. (In the case of Figure 2c, there are some regions where the magnetic field lines are wound up though the regions have only weak magnetic field. This may be related with the behavior and structure of the magnetic field of part of AR's of inverted polarity which have been discussed in connection with the flare-productiveness (Zirin, 1970). In the longitudinal regions where the magnetic field is intensified most near the surface, however, the field lines are regular and are not wound up.) Moreover the latitudinal-longitudinal structure and the radial-longitudinal structure of the fields in Figure 2 in the regions of the magnetic field intensified most near the surface have the features which explain the general basic characteristics of AR's in an analogous but more pronounced way than in Figure 1.

What should be noted here is that as the pattern of the velocity and magnetic fields of the global convection propagates eastward with respect to the averaged fluid of the convection zone, the sources and the sinks of the convection at the surface also propagate with respect to the fluid. Hence the places of favorable appearance and of disappearance of AR's also propagate. Therefore the AR's which float on the flow of the convection may experience both the sources and the sinks many times during their life time if the AR's live long. Thus the rejuvenation of an older AR (Weart, 1972) is a natural consequence when the AR comes to the source regions. The circumstances stated above mean also that simple distribution of AR's or sunspots may not display the pattern of the convection. In order to know the pattern, the distribution of AR's or sunspots with particular characteristics should be studied.

5. Concluding Remarks

We have shown that the several basic characteristics of AR's, i.e., the tilts of the bipolar axes of sunspot groups, the inclination of normal axes of sunspots, the asymmetry of magnetic field strength between the preceding and following spots, the difference of the rotation rate between the sunspots and the averaged fluids, and the association of the proper motions and the asymmetry of an AR with the relative disposition of the AR and an older AR in the vicinity, can be understood naturally if we consider that they are just the reflections of the velocity and magnetic fields structure of the convection zone below AR's. We need not the concepts of the twists of magnetic flux tubes and of the radial stratification of the differential rotation so far as concerning the above phenomena. Instead the velocity and magnetic fields of the whole convection zone are twisted and are made wave-like by the actions of the global convection and the rotation. The concept of the tubes must be introduced when we consider the formation and appearance of sunspots at the surface. The formation of AFS's and/or AR's in the upper region of the convection zone is not yet so clear. The actions of supergranulations and of magnetic buoyancy may be its main cause.

The fact that there are two categories of sunspots and sunpots groups with respect to the characteristics stated above which are closely intercorrelated each other can be explained in a unified manner by the concept that AR's occur in the forward going flow of the global convection and in the backward going flow of the convection as well. The characteristics of the AR's depend on whether the AR's occur in the forward going flow or in the backward going flow of the global convection. As the AR's tend to live longer in the forward going flow than in the backward going flow due to the effect of the rotation, the characteristics of the AR's in the forward going flow become prominent in the solar AR's as a whole.

To comment on the tilt of axes of bipolar sunspot groups as the cause of the regeneration action of the solar dynamo used by Babcock (1961) and Leighton (1969) in their magneto-kinematical solar cycle model, though the tilt can be an evidence that the Coriolis force acts on the dynamics which determines the magnetic field structure of the convection zone, it may not be the direct cause of the solar dynamo which governs the structure of the main body of the zone if the interpretations in this paper are adopted, because as is shown in this paper the tilt is caused by the longitudinal and latitudinal correlation of the fields at the surface while the regeneration action of the solar dynamo is caused by the radial and latitudinal correlation of the fields (Yoshimura, 1972b).

The fact that the characteristics of AR's reflect the magnetohydrodynamical structure of the convection zone deep below the AR's shows that the magnetic field lines of the AR's are connected directly with the general magnetic fields of the deep convection zone.

In conclusion, it has been shown that it is possible to infer the deep structure of an AR by the structure and state of the global convection which has been conceived and investigated from the standpoint to explain the global behavior of the velocity and magnetic fields and of the solar activity. Conversely, by studying the characteristics of the structure and evolution of AR's, it will be possible to understand the magnetohydrodynamical state of the convection zone below the AR's and hence the state of the global convection and the convection zone as a whole.

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References

Alfvén, H.: 1950, *Tellus* **2**, 74.
Ambrož, P., Bumba, V., Howard, R., and Sýkora, J.: 1971 , in R. Howard (ed.), 'Solar Magnetic Fields', *IAU Symp.* **43**, 696.
Babcock, H. W.: 1961, *Astrophys. J.* **133**, 572.
Brunner, W.: 1930, *Astron. Mitt. Zürich*, No. **124**, 67.
Bruzek, A.: 1967, *Solar Phys.* **2**, 451.
Bruzek, A.: 1968, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions' *IAU Symp.* **35**, 293.
Bruzek, A.: 1969, *Solar Phys.* **8**, 129.
Bumba, V.: 1963, *Bull. Astron. Inst. Czech.* **14**, 91.
Bumba, V. and Howard, R.: 1969, *Solar Phys.* **7**, 28.
Busse, F. H.: 1970, *Astrophys. J.* **159**, 629.
Davies-Jones, R. P. and Gilman, P. A.: 1970, *Solar Phys.* **12**, 3.
Deinzer, W.: 1965, *Astrophys. J.* **141**, 548.
Dodson, H. W. and Hedeman, E. R.: 1968, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions', *IAU Symp.* **35**, 56.
Dungey, J. W.: 1958, *Cosmic Electrodynamics*, Cambridge University Press, Cambridge, p. 56.
Durney, B.: 1970, *Astrophys. J.* **161**, 1115.
Ellison, M. A.: 1944, *Monthly Notices Roy. Astron. Soc.* **104**, 22.
Foukal, P.: 1972, *Astrophys. J.* **173**, 439.
Gilman, P.: 1972, *Solar Phys.* **27**, 3.
Grotrian, W. and Künzel, H.: 1950, *Z. Astrophys.* **28**, 28.
Hale, G. E.: 1913, *Astrophys. J.* **38**, 27.

Hale, G. E. and Nicholson, S. B.: 1938, *Magnetic Observations of Sunspots*, Carnegie Institution of Washington Publications No. 498.
Howard, R. and Harvey, J.: 1970, *Solar Phys.* **12**, 23.
Leighton, R.:1969, *Astrophys. J.* **156**, 1.
Lundqvist, S.: 1951, *Phys. Rev.* **83**, 307.
Martres, M. J.: 1970, *Solar Phys.* **11**, 258.
Martres, M. J. and Soru-Escaut, I.: 1971, *Solar Phys.* **21**, 137.
Maunder, A. S. D.: 1907, *Monthly Notices Roy. Astron. Soc.* **67**, 451.
Minnaert, M.: 1946, *Monthly Notices Roy. Astron. Soc.* **106**, 98.
Newton, H. W. and Nunn, M. L.: 1951, *Monthly Notices Roy. Astron. Soc.* **111**, 413.
Sawyer, C. and Haurwitz, M. W.: 1972, *Solar Phys.* **23**, 429.
Simon, G. W. and Weiss, N. O.: 1968a, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions', *IAU Symp.* **35**, 108.
Simon, G. W. and Weiss, N. O.: 1968b, *Z. Astrophys.* **69**, 435.
Švestka, Z.: 1968a, *Solar Phys.* **4**, 18.
Švestka, Z.: 1968b, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions', *IAU Symp.* **35**, 287.
Waldmeier, M.: 1937, *Z. Astrophys.* **14**, 91.
Ward, F.: 1965, *Astrophys. J.* **141**, 534.
Weart, S. R.: 1970, *Astrophys. J.* **162**, 987.
Weart, S. R.: 1972, *Astrophys. J.* **177**, 271.
Weart, S. R. and Zirin, H.: 1969, *Publ. Astron. Soc. Pacific* **81**, 270.
Weiss, N. O.: 1966, *Proc. Roy. Soc. London* **A293**, 310.
Yoshimura, H.: 1971, *Solar Phys.* **18**, 417.
Yoshimura, H.: 1972a, *Solar Phys.* **22**, 20.
Yoshimura, H.: 1972b, *Astrophys. J.* **178**, 863.
Yoshimura, H. and Kato, S.: 1971, *Publ. Astron. Soc. Japan* **23**, 57.
Yun, H. S.: 1970, *Astrophys. J.* **162**, 975.
Zirin, H.: 1970, *Solar Phys.* **14**, 328.