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Unique Complex of Activity between 2006 and 2007

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Abstract—The main characteristics of the Sun's complex of activity (CA), observed between 2006 and 2007, have been considered. The main CA sunspot existed during almost five solar rotations and did not shift in the Carrington coordinate system. The model, according to which CA developed on the basis of a stable large-scale convection cell that reached the convective zone bottom, has been proposed.

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1. INTRODUCTION

The Sun's CAs represent one of the solar activity organization levels between active regions (ARs) and active longitudes. The phenomenon essence consists in that the system of closely interrelated ARs, originating simultaneously and (or) successively, exists during a prolonged period (several solar rotations) in a certain zone of the Sun's surface. As a result, several tens of individual ARs can originate within CA during the entire period of its existence (up to 17 rotations). CA is a unified evolving physical system of several ARs integrated by the system of magnetic fields. The structure, evolutionary characteristics, and statistics of CAs were considered in [Banin and Yazev, 1989; Yazev, 1990, 1999].

Central parts (CA cores), which are the zones where sunspots of successively originating ARs during several solar rotations constantly exist, can be distinguished in CAs. It was indicated [Yazev, 1991] that CA cores have the following important property: they are not subjected to differential rotation during the period of sunspot existence, and such a rigid rotation of CA cores takes place with a Carrington velocity. When sunspots disappear, the residual CA magnetic fields spread under the action of differential rotation.

These features of CA rotation should be explained. The problem was considered here using CA, which was observed between 2006 and 2007 and had several specific features, as an example [Savinkin and Yazev, 2008]. Below, we briefly describe certain properties of the above CA and the model that is aimed at explaining these properties.

2. STRUCTURE AND EVOLUTION OF CA BETWEEN 2006 AND 2007

This CA was based on a large long-lived sunspot that existed from the end of October of 2006 to February of 2007, which is an extremely rare phenomenon (analogs are absent at least in solar cycle 23). During this period, the sunspot almost did not move in the Carrington coordinate system ($L = 8°$, $\varphi = -7°$). Figure 1 shows the sunspot evolution and position in the Carrington coordinate system: the upper panel of Fig. 1 corresponds to the November passage of CA over the disk; the second panel, to the December passage, and so on until the February passage. A small group of pores still existed in the sunspot position in March.

During the first rotation, the sunspot rotated first counterclockwise and then clockwise with an average velocity of an angular minute per hour [Savinkin and Yazev, 2008]. During the second rotation (December 2006), the rotation slowed down (to 11 arcmin/h), and the umbra rotated a factor of 1.5 as rapidly as the penumbra [Savinkin and Yazev, 2008]. A new umbra zone was formed within the general penumbra, after which a new sunspot separated from the initial one. According to the SOHO spacecraft data, a giant system of high loops, which reached altitudes not lower than 300 thousand kilometers and extended to approximately 300 thousand kilometers northward and 200 thousand kilometers southward from CA, was observed in CA that was based on AR no. 10930 in the UV region at that time. AR included the former large sunspot and small sunspots and pores from west and south (the maximal number of sunspots was 17, and the maximal sunspot area was 680 m.d.p. [Ishkov, 2006a]).

The series of large flares took place in CA during that period [Ishkov, 2006b]. The X/4 + M/5 +C/48 X-ray flares and 3/1 +2/3 +1/4 +S/51 optical flares occurred in CA during the second passage over the disk. The X9.0/2N X-ray flare of December 5, 2006 (the 8th place with respect to power in cycle 23), X6.5/3B flare (the 13th place in cycle 23), X3.4/2B flare of December 13, 2006, and X1.5/1N flare of December 14, 2006, attract special attention [Ishkov, 2006b]. Even taking into account an example of an unusual X2.6/1B flare that occurred in July 1996 during the cycle minimum phase [Ishkov, 2006b], high flare activity of the considered CA during the preminimum cycle stage looks unprecedented. It is logical to assume that this activity is related to the above dynamic processes in the main CA core caused by the departure of a new magnetic flux in the main sunspot penumbra on December 9–13, 2006.

We can note that certain parameters of the considered CA and several ARs described in [Makarova et al., 2001] are similar. It was indicated here that new sunspots also emerged within the penumbra of the existed sunspot of the δ configuration in the studied flare-active ARs, powerful flares occurred after the maximal turn of the sunspot group, and the sense of rotation changed after the flares. We note that the regions studied in [Makarova et al., 2001] were observed during the solar activity maximum stage (1989–1991); in our case we have a similar example during the cycle preminimum stage.

After the burst of solar activity on December 5–14, 2006, the sunspot started decreasing beginning from December 16, 2006, and the CA general magnetic structure became simpler.

New AR (the western branch of CA at $L = 39°$, $\varphi = -4°$), which composed the unified system with the old branch judging by the magnetic field distribution topology, was observed during the third, fourth, and fifth rotation 30° west of the considered AR. A new CA branch differed in the non-Carrington rotation velocity (AR shifted by approximately 5° westward during a rotation). The main AR sunspot of a new branch had an anomalous magnetic polarity and rotated at the same velocity as the main long-lived sunspot of an old (eastern) CA branch (14 arcmin/h) but in the opposite direction. The CA structure and evolution were described in more detail in [Savinkin and Yazev, 2008].

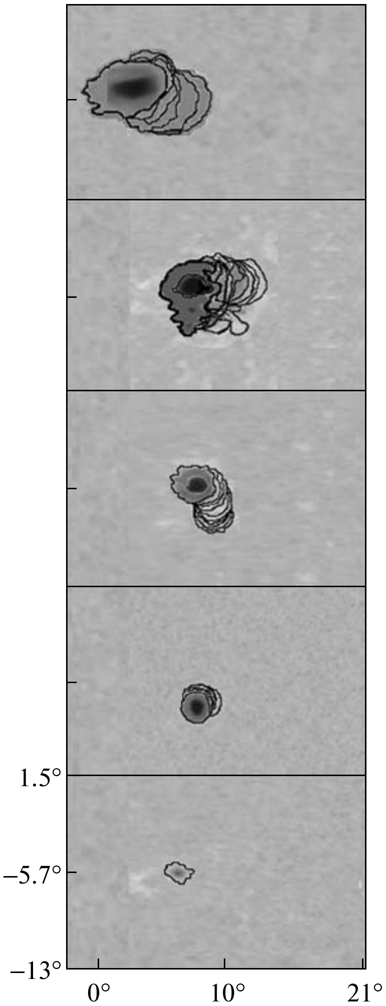

Fig. 1. Evolution and displacement of the main CA sunspot in the Carrington coordinate system during five passages over the disk.

3. CA MODEL BASED ON THE LARGE-SCALE CONVECTION CELL

We assume that the main features of the considered CA (prolonged existence of the main sunspot and its stable position in the Carrington coordinate system) can be explained in the scope of the following model.

According to the proposed hypothesis, CA was formed based on the large-scale convection cell [Simon and Weiss, 1968] extending from the photosphere to the convective zone bottom (tachocline level) [Yazev and Sidorov, 2007]. In this case plasma flows at the cell periphery are directed downward, and the motion is directed toward the cell center near the bottom. Since the magnetic field (MF) is frozen-in at the cell center, MF is concentrated near the cell bottom. Magnetic buoyancy accelerates successive floating of a matter and MF loops at the cell center. As a result, CA develops at the photospheric level and higher and as a rule includes several ARs, which are successively or simultaneously formed at the cell center as the next magnetic flux portions emerge. The general character of the described motions does not contradict the data on the velocity field deep in the convective zone obtained using the helioseismological methods [Kosovichev, 2007].

It is assumed that the considered CA was formed based on the described convection cell during the preminimum solar activity phase under the conditions of symmetrical and homogeneous MF without adjacent disturbing structures. Following convective motions, MF at the cell periphery submerges and is concen-

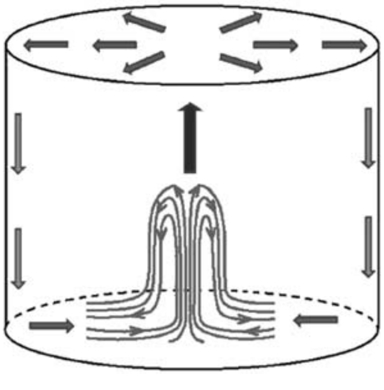

Fig. 2. Motions in the symmetric large-scale convection cell during the solar cycle pre-minimum stage. Thick and thin arrows show the matter and MF directions of motion, respectively.

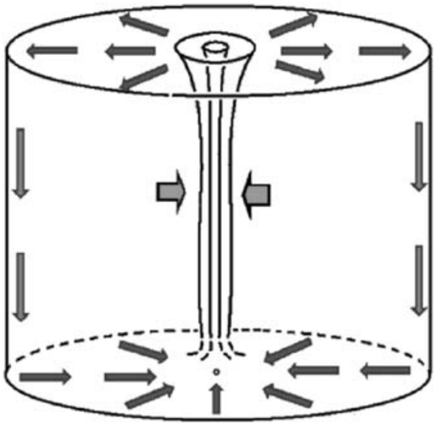

Fig. 3. The lift structure at the cell center: the central unipolar zone and the surrounding quasi-cylindrical cell. Concentrated MF emerges here, and this field is mostly potential and non-potential in the central zone and in the cylindrical cell, respectively.

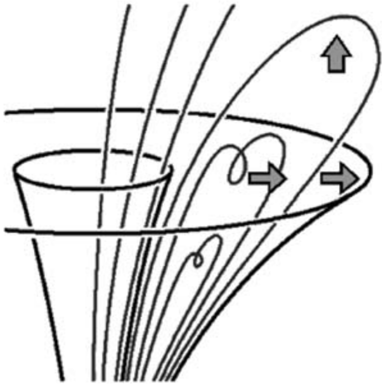

Fig. 4. The emergence of MF loops in the quasi-cylindrical cell. The intersection of the photospheric level by field lines results in the apparent disappearance of magnetic feature pairs of different signs.

trated near the cell center at its bottom. This field showed a high degree of circular symmetry, which is responsible for the specific feature of this CA. The MF structure in CA is close to dipole, and the field strength is maximal near the axis of symmetry coincident with the cell magnetic dipole axis. The upward plasma motion with the maximal velocity near the vertical axis twists field lines around this axis, which results in an additional local field strengthening. As a result, the vertical channel of a relatively fast plasma lift from the convective zone bottom (a high-velocity lift, see Fig. 2) is formed at the cell center. The velocity of lift of the plasma with frozen-in MF increases here owing to magnetic buoyancy. The channel becomes narrower with increasing lift velocity. The general magnetic structure is similar to a tree, where a vertical stem and a crown with a more complex structure can be distinguished. It is reasonable to distinguish three regions of a large-scale cell (Fig. 3): the central part (a stem) with unipolar, mostly potential, MF; the surrounding quasi-cylindrical shell (a crown) including a field with a large non-potential component; and the remaining outer volume of a cell with relatively weak fields.

The prolonged conservation of the field vertical structure in the central part makes it possible to assume that the MF energy density is higher here than the energy density of tangential plasma motions. As a result, the field is mostly potential here.

The field of a cylindrical shell is composed of many successively and simultaneously emerging small-scale MF loops with the considerable non-potential field component caused by close energy densities for MF and tangential plasma motions. Here (and only here) the convective motion energy is partially transformed into the MF non-potential motion. Emergence and spread of the plasma with the frozen-in field in the cylindrical shell at the photospheric level is observed on the SOHO magnetograms as moving magnetic features or MMF of both polarities from the sunspot center outward [Ravindra, 2006]. An apparent annihilation of MMF pairs with opposite polarities is explained in the scope of the considered model by a lift of spiral magnetic loops into the corona (Fig. 4).

When the field appears in the corona, the non-potential energy is accumulated in the coronal loops and is subsequently released in the series of powerful solar flares. During flares, energetic particles precipitate along the MF lines from the corona into the chromosphere only in the zones of the chromosphere through which the non-potential MF energy entered into the corona. This can explain the known fact that the flare emission is mostly not observed at the sunspot umbra center (the field is mainly potential here).

In the proposed scheme, MF emerging in the quasi-cylindrical shell is a specific lift for the matter trapped during its motion. A high degree of the MF distribution symmetry in the entire cell volume results in the formation of a stable channel for the MF non-potential energy escape into the corona. An increased velocity of energy release from a compact cylindrical shell into the corona creates the conditions for generation of powerful solar events.

4. CONCLUSIONS AND DISCUSSION

As was indicated above, the fact that CA is not subjected to differential rotation in the scope of the considered scheme is related to a high stability of the long-lived large-scale convection cell that reaches the convective zone bottom. Precisely the latter circumstance resulted in that the cell did not move in the Carrington coordinate system and was responsible for the stable position of the main sunspot at the cell center. It is not improbable that the formation of such a cell is related to specific seed inhomogeneities at the tachocline level. Note that the Carrington rotation velocity of the sunspot during almost five months can be explained only by the existence of the physical relation between the sunspot and the non-differentially rotating convective zone bottom, especially taking into account the sunspot center low latitude for which a higher rotation velocity is typical according to the differential rotation laws.

The alternative viewpoint made it possible to assume that CAs are related to the MF systems rooted even at the convective zone bottom [Piddington, 1975]. However, the present-day data on helioseismology indicate that sunspots should be considered relatively surface formations, and the related inhomogeneities apparently do not extend to such depths [Ravindra, 2006]. From this we can conclude that refined models of magnetic trees, proposed by Piddington [1975] in order to explain all types of photospheric MFs, should apparently be acknowledged inapplicable. On the other hand, convective motions at the cell center in the scope of the model proposed by us create here a special MF configuration. We should admit that this configuration in a certain sense revive the Piddington ideology on the other physical basis, assuming that large-scale convective flows play the main role here.

The existence of the discussed cell apparently promoted the formation of one more cell west of the previous one two solar rotations later, and this new cell generated new AR. The vertical scale of the second (new) call was apparently smaller (without a contact with the convective zone bottom), as a result of which AR moved here westward by 5° during a rotation according to the laws of differential rotation at the photospheric level. The fact that the CA fields were deeply rooted and other ARs were absent probably caused high stability of the main sunspot in the first cell and the entire CA. The successive appearance of new magnetic flux portions in the corona in the same place with the sunspot of long-lived different-age MF loop systems was responsible for the generation of powerful flares in December of 2006. A rare example of the CA development during the pre-minimum cycle phase can be considered as a convenient refined case for analyzing the CA evolution in the absence of the effect of adjacent structures. In other cases of CA development, the situation is apparently more complex with regard to the effect of interaction between adjacent cells of different scales, which should also result in a more complex MF distribution structure.

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