Global complexes of activity

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M.N. Gnevyshev (1938) proved convincingly that, in addition to the general 11-year solar-activity cycle, there are short-term periods of increased activity, which he called “pulses of activity”.

H.W. and H.D.Babcock (1955) were the first to study the distribution of the magnetic fields outside sunspot groups. They discovered two systems of magnetic fields at lower latitudes: bipolar magnetic regions, corresponding to active regions, and unipolar magnetic regions, which are extensive areas of magnetic field of a single polarity.

Bumba and Howard (1965) showed that a complex evolves as follows. Within a certain longitude range, no activity is observed for several solar rotations except the diffuse fields of old active regions. Then, one or more new active regions appear and begin to expand gradually in both latitude and longitude. The first group to appear is usually the largest in a complex. Larger complexes have longer lifetimes and contain groups that are larger in size.

It is very important for further discussion that these authors supposed implicitly that an activity complex should include both active regions and unipolar magnetic regions. This means that one must also consider coronal holes and introduce the concept of a global activity complex. *The goal of this work is to establish the concept of a global activity complex that incorporates objects associated with both local and global fields.*

An additional difficulty that arises in analyzing global complexes of activity is the need to take into account the interaction of fields of different spatial scales and with different intensities. There is no doubt that large-scale fields are associated with the global magnetic field (*Obridko and Shelting, 2000, 2003, Ivanov and Obridko, 2002, Demidov and Grigoryev, 2004*) and their evolution is likely to be controlled by processes deep beneath the photosphere, possibly at the base of the convection zone. On the other hand, the structure of a complex depends strongly on the evolution of intense, shallow fields of active regions lying at depths of 5–10 Mm.

The genetic relation between the components of a complex is not clear. On the one hand, large-scale fields are intensified by subsurface flows and appear to provide the building material for the fields of active regions. On the other hand, the weak magnetic fields remaining after the decay of active regions also form extended features that merge with the primary large-scale field.

It should be noted that the relationship between the open field regions (OFR) and CHs is quite clear, and the use of these terms as equivalent is physically justified. However, analogous correspondences between other objects are not so evident. Many authors identify large quasi-unipolar regions (UR) with open field regions and determine CH boundaries just as the boundaries of UR. This approach has no physical grounding. Large quasi-unipolar regions may merely be remnants of former active regions. The field in such objects is shallow, and the field lines close inside the same region. They do not form OFR, and have the unipolarity index much less than unity. This should be borne in mind in further comparisons.

In the process of their evolution, the large-scale magnetic field, CH, and active region form a single complex with the following properties. Regions where the magnetic field in the chromosphere and lower corona departs from the radial direction by less than 20° *are sources of optical and* X-ray CHs. In spite of the physical identity of the two objects, their boundaries may not coincide, and there may be a delay in the appearance of the CH relative to the appearance of the open field regions .

After two or three rotations following the appearance of a CH, its shape and size begins to change under the influence of the active regions situated between the conjugate CHs. As a result, a saddle-type feature appears in the transverse field at the photosphere level near the CH boundaries.

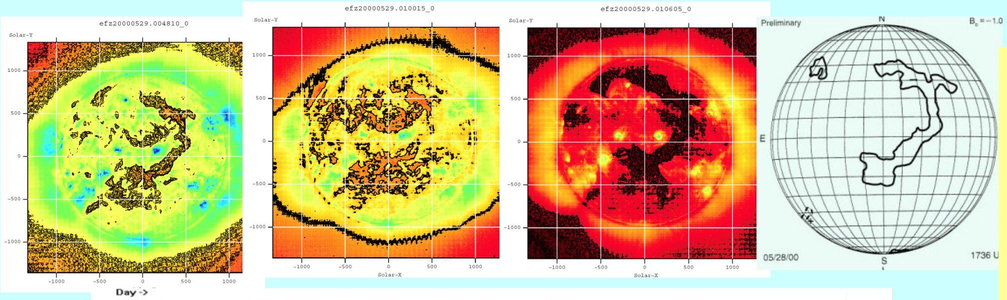
Outside the photometric CH, the magnetic vectors converge to the conjugate active regions to form a single activity complex. This effect is particularly pronounced for large active regions. The relationship between large active regions and CHs was noted by *McIntosh (1992)* and *Bumba, Klvana, and Sykora (1995).* A major AR complex associated with the X-ray coronal hole was observed in the southern hemisphere in September-October 1991 and was analyzed by *Mogilevsky and Shilova (1994, 1996*).

This relationship exists despite the fact that the source of the large-scale magnetic field lies deep at the bottom of the convection zone *(DeLuca and Gilman, 1991),* and the spots in active regions are known today to be much more shallow features.

The lifetimes of CHs range from 1-2 rotations to 1.5 years, exceeding those of the related active regions. As the active regions decay or disappear, the CHs change accordingly.

The data used

Comparison of the positions of CHs with those of active regions involves certain difficulties. It is not entirely clear *a priori* what should be considered the boundary of a CH, even when it is observed at the same wavelength.



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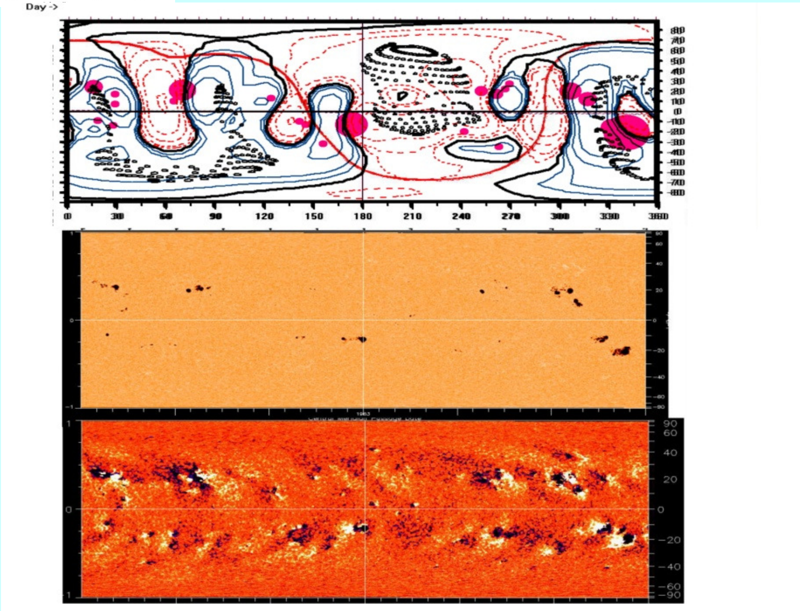
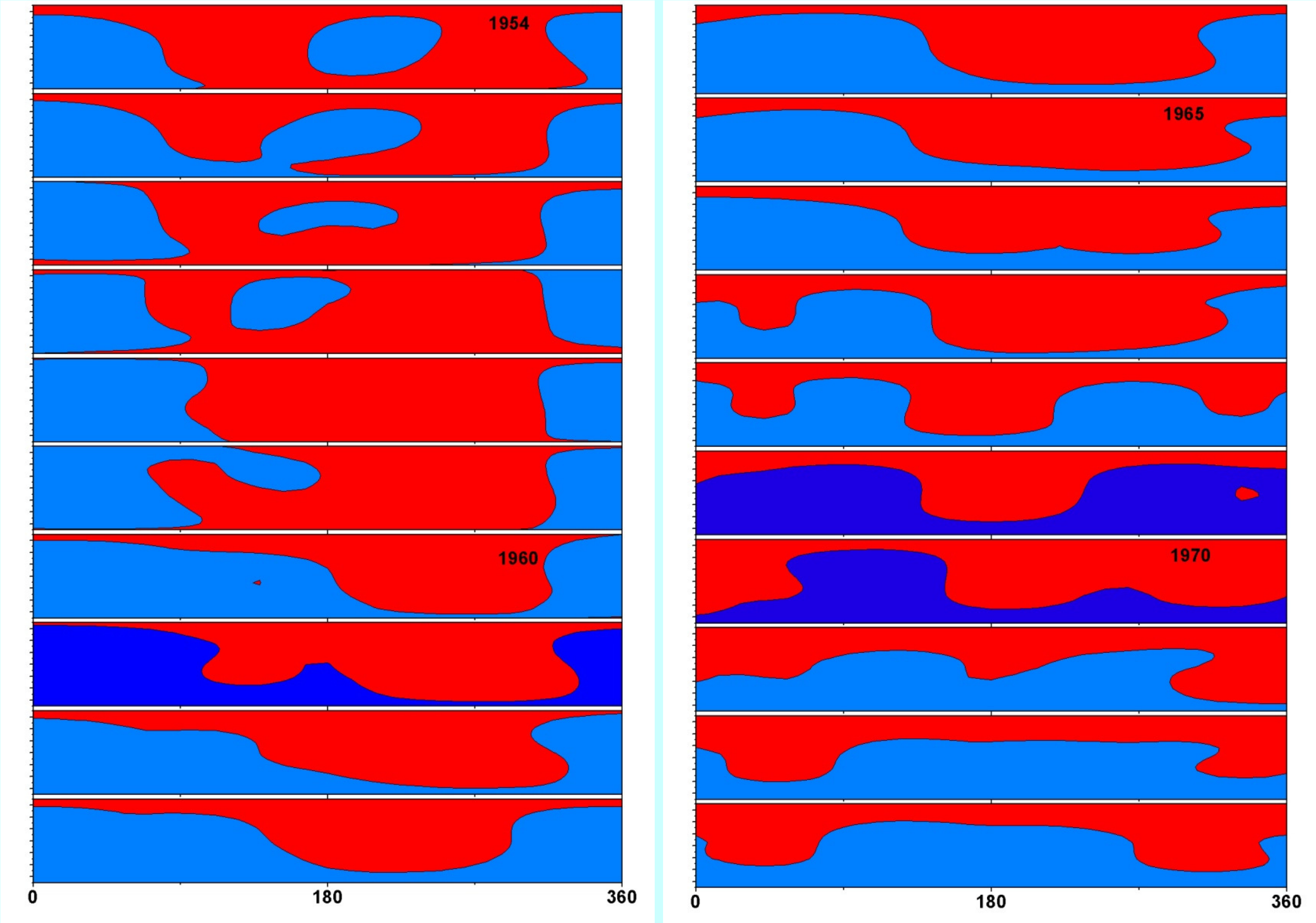
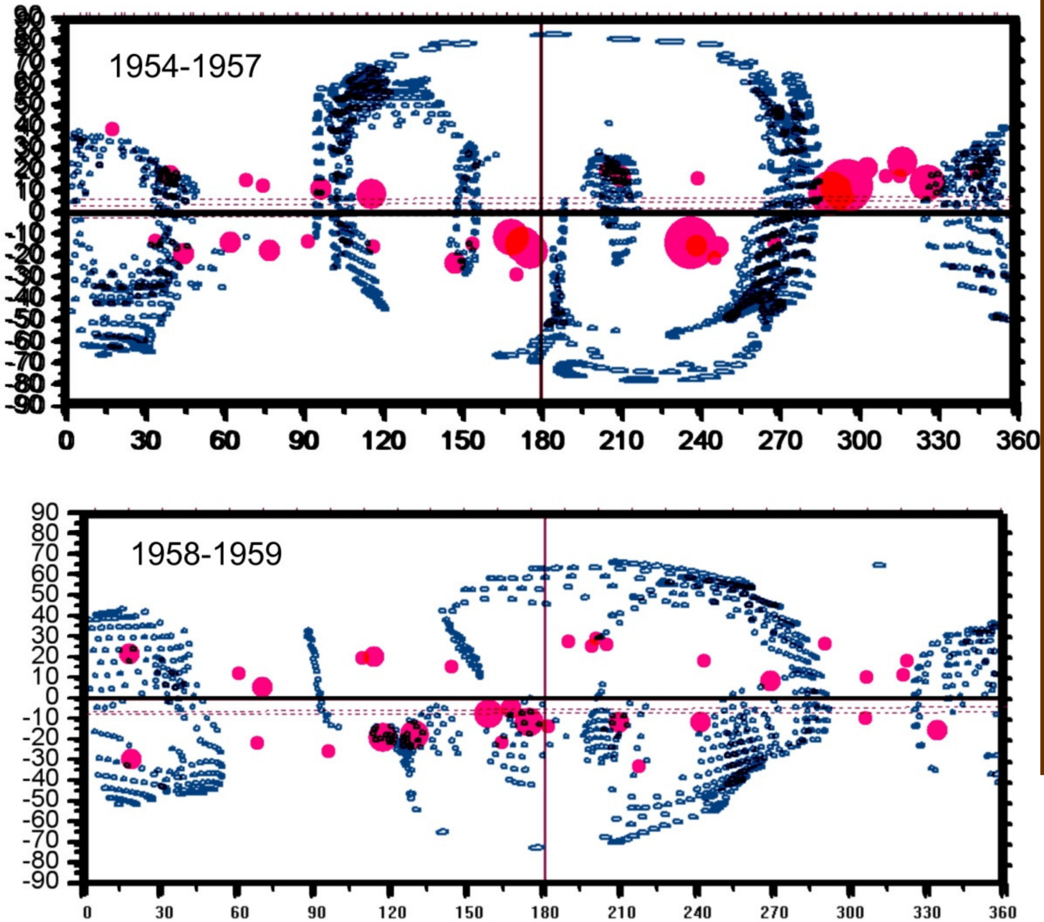


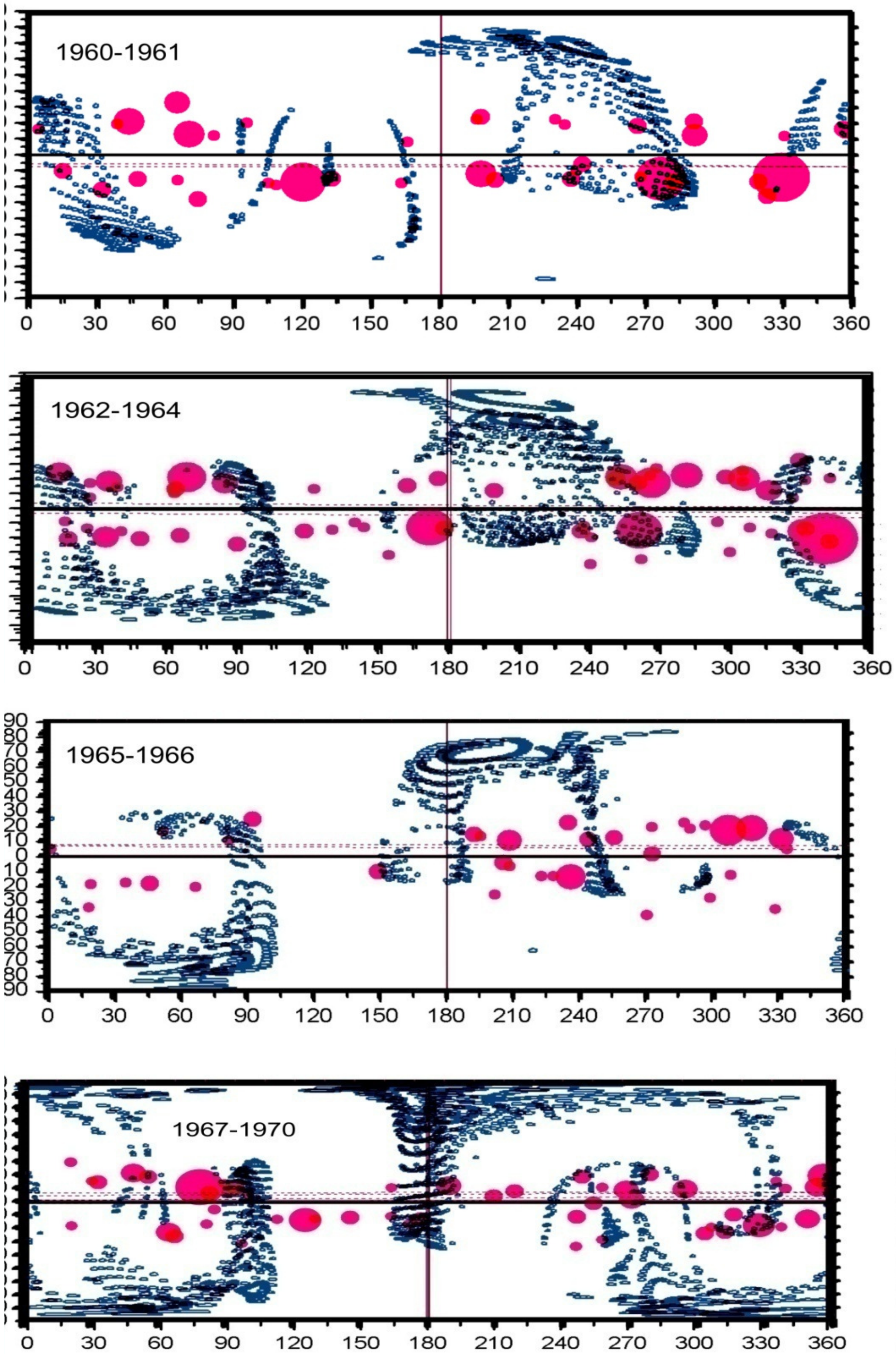


Unfolded pattern of the large-scale magnetic field on the source surface for the period from September 1999 to December 2001 (rotations 1954-1973). The abscissa shows the longitude and the ordinate, the latitude in each rotation. The fairly complicated pattern corresponds to the period after reconnection of the polar field in the vicinity of the cycle maximum.



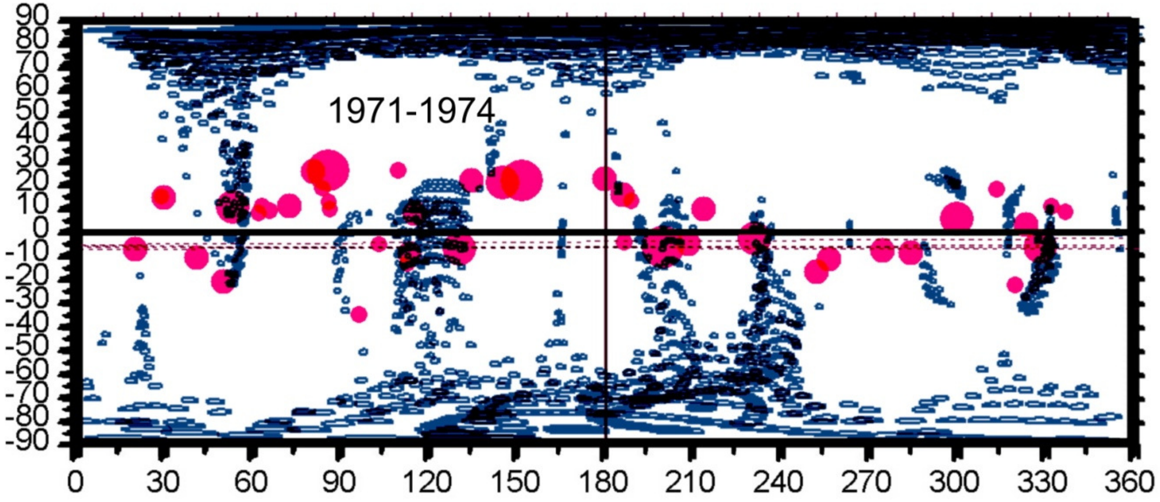
The figure shows OFR synoptic maps divided for convenience into seven periods, each characterized by relatively similar and stable structure. At the beginning of the period (rotations 1954–1957), one can see six OFR forming two giant complexes. At the center of the map, at longitudes of 120−270˚ (complex 1), there are fairly large compact regions connected with each other and with the polar zones. At longitudes of 330−30°, there is another OFR that is more loosely structured and less extensive (complex 2). In the vicinity of OFR, we can see active regions, the largest of which lie directly on the boundary of the central OFR.

In rotations 1958–1960, the OFR become more loosely structured and are rather weakly pronounced. The connection with the polar zone disappears. Simultaneously, the level of solar activity decreases. There are numerous active regions, but no large ones among them.



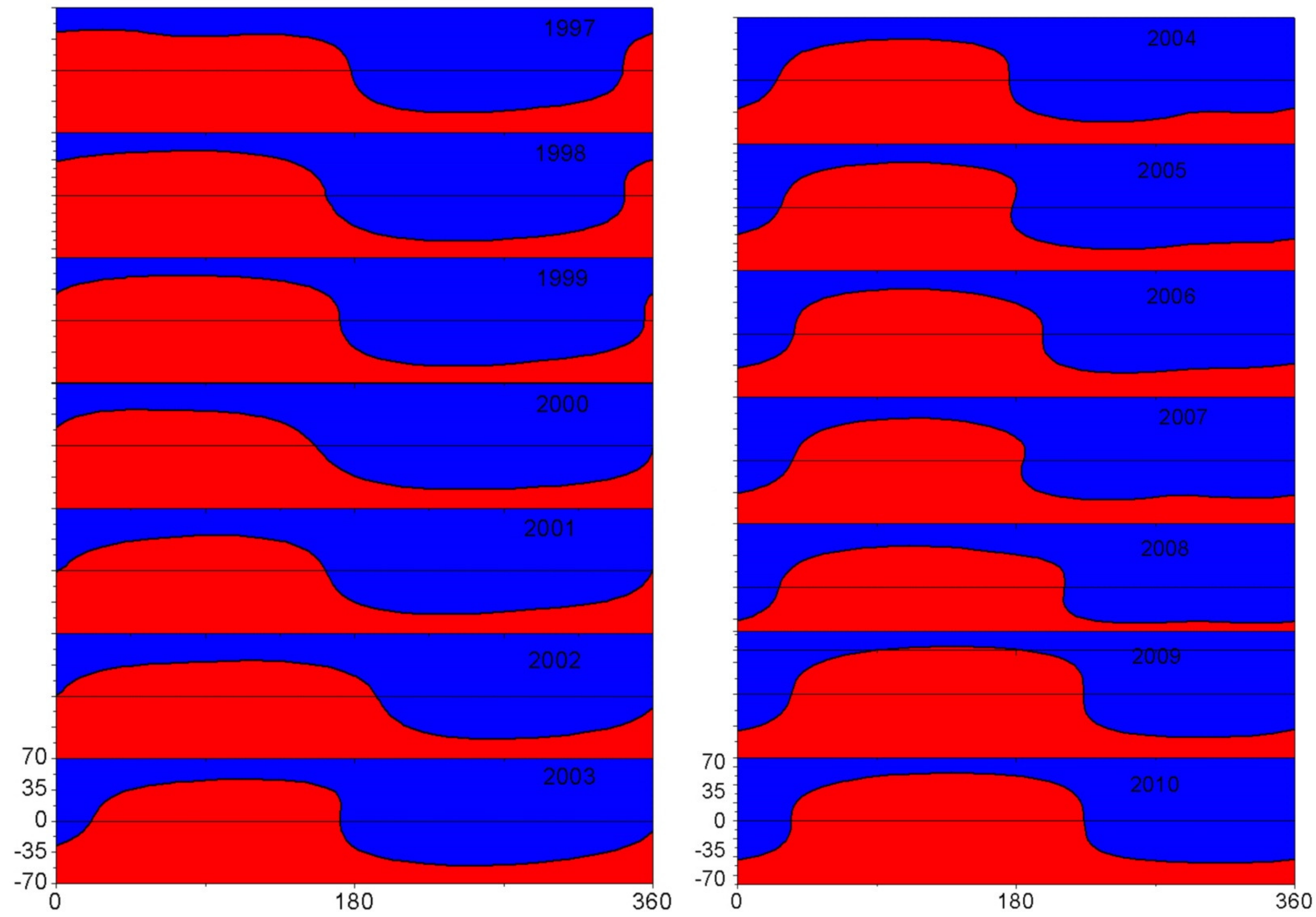
In the next period (rotations 1960–1961), the configuration begins to change. The first complex becomes narrower and more compact. Its center of gravity shifts toward longitudes 210°−270°. In addition, thin strips of OFR appear in the range 60°−120°. The large active regions are mostly located in the vicinity of OFR.

In the course of variations described above, the second complex remains at the same place, but its center of gravity shifts toward longitudes 30°−60°. Complex 2 expands and intensifies most strongly beginning from rotation 1960, and many active regions appear inside it simultaneously. Later, C2 remained almost unchanged until the end of the interval under consideration. With the increase of the number of active regions in rotation 1960, the giant complex 2 divided into two equal parts, with a unipolar region of opposite (negative) polarity wedged between them. However, a CH did not arise therein.

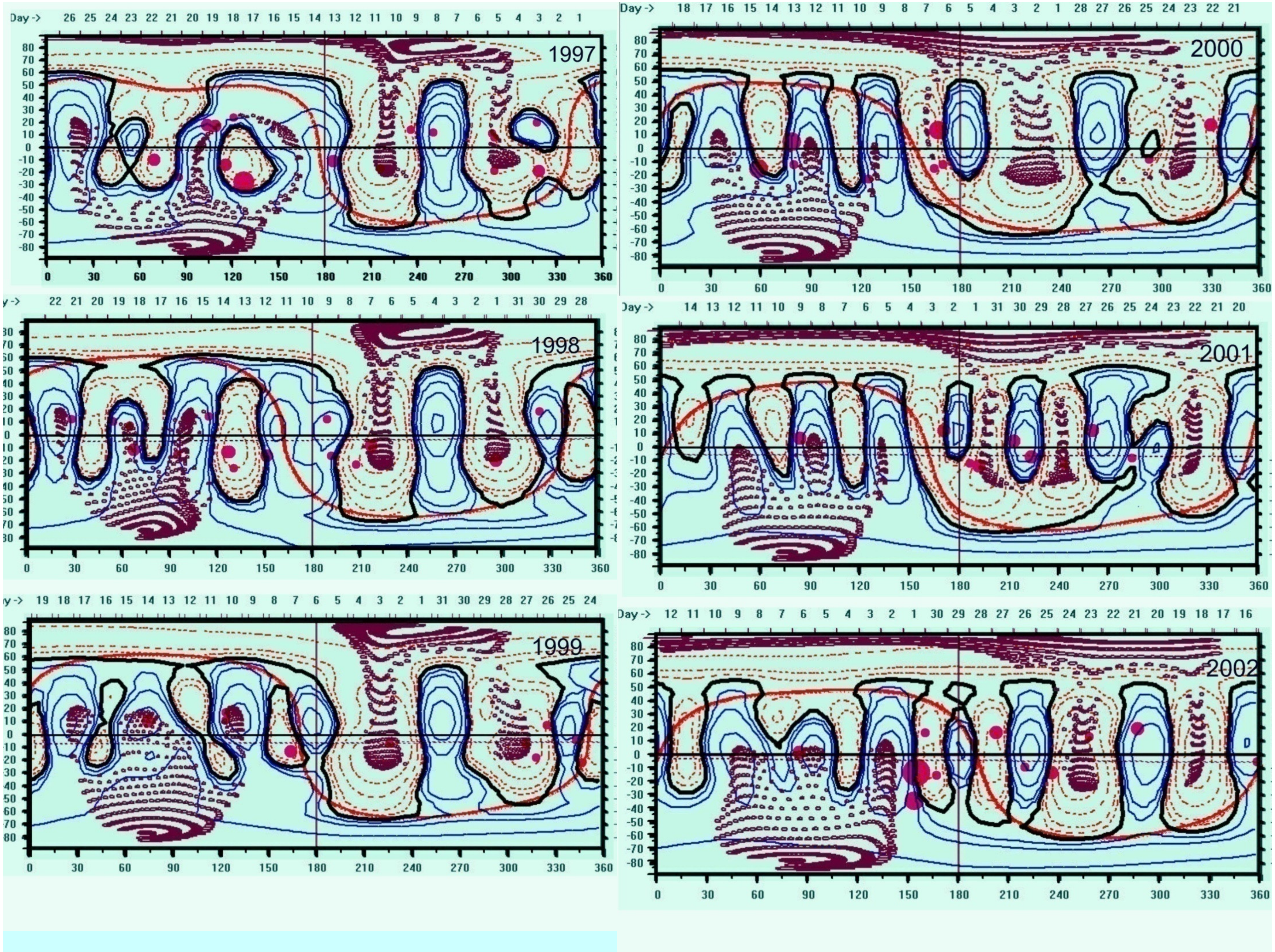


In the last four rotations (1971–1974), the open field regions became isolated and small in size, occasionally emerging and vanishing, and their relationship to active regions became less clear.

Further, the OFR decay gradually in the equatorial zone, nearly vanishing there by the end of the period.



Unfolded pattern of the large-scale magnetic field on the source surface for 2003 (rotations 1997-2010). The abscissa shows the longitude and the ordinate, the latitude in each rotation. The pattern corresponds to the simple equatorial dipole co-rotating with the Sun.



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2000
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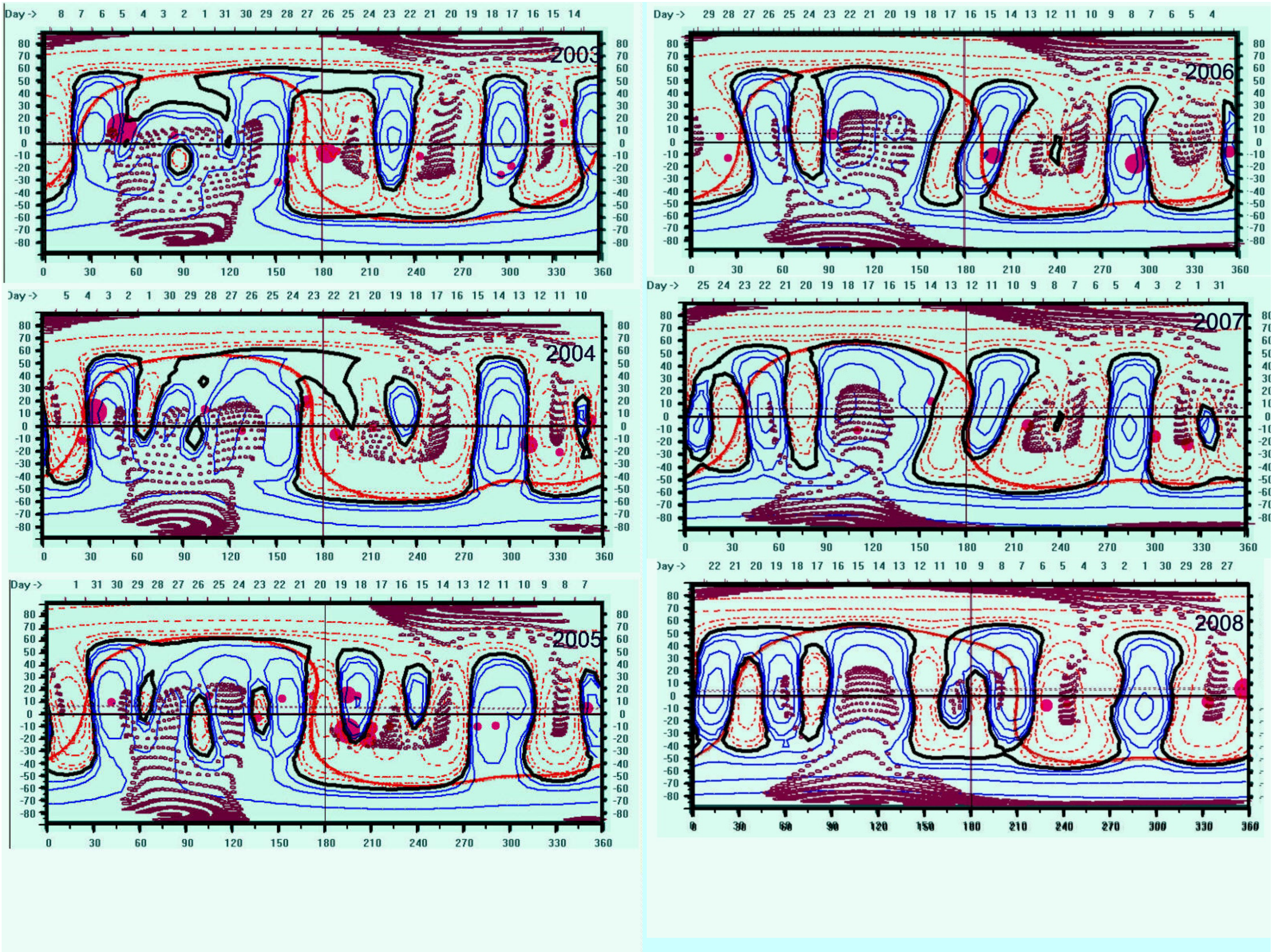
2003
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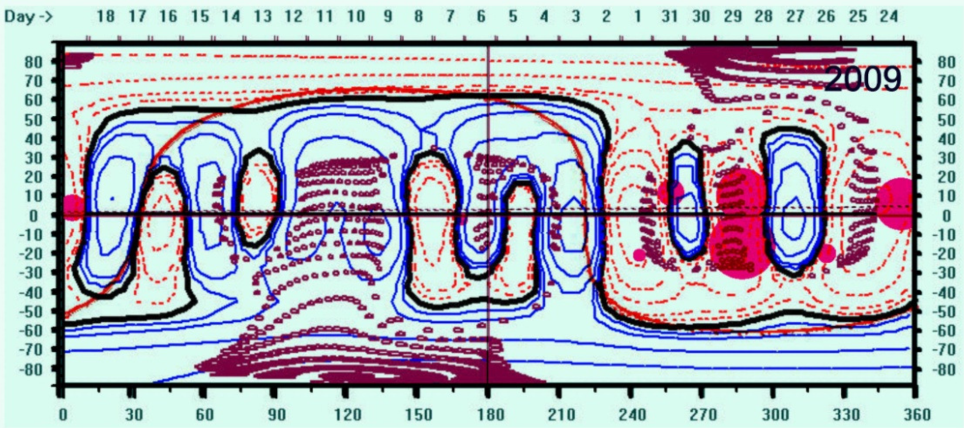
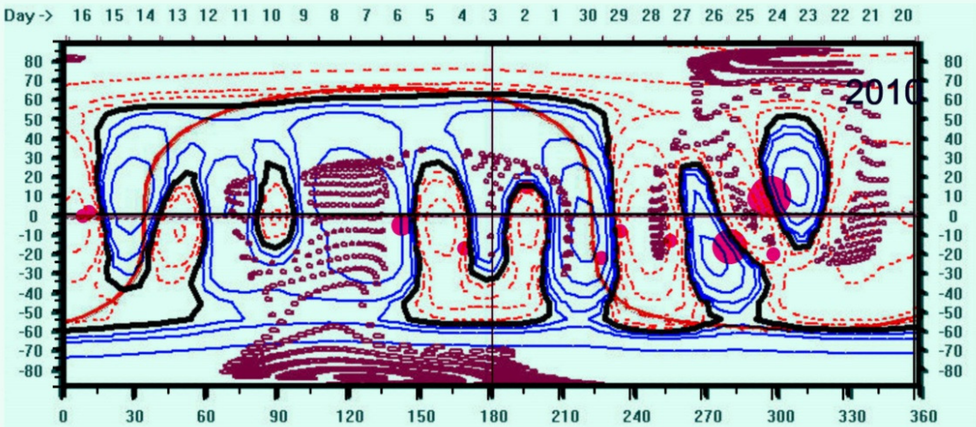
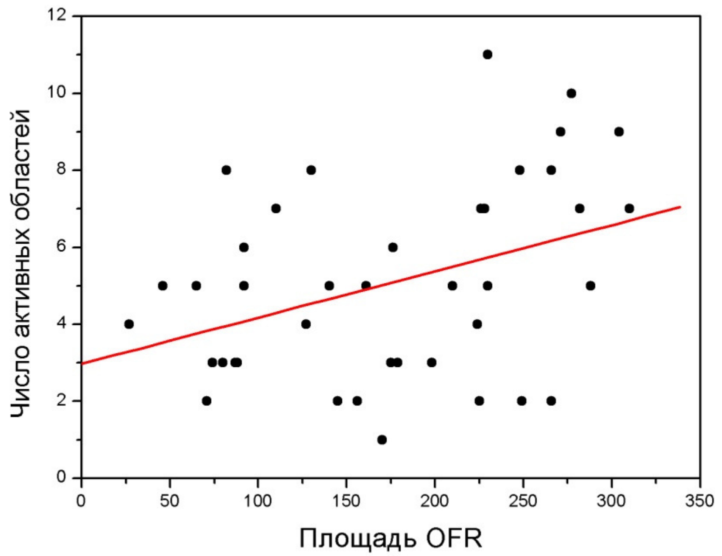


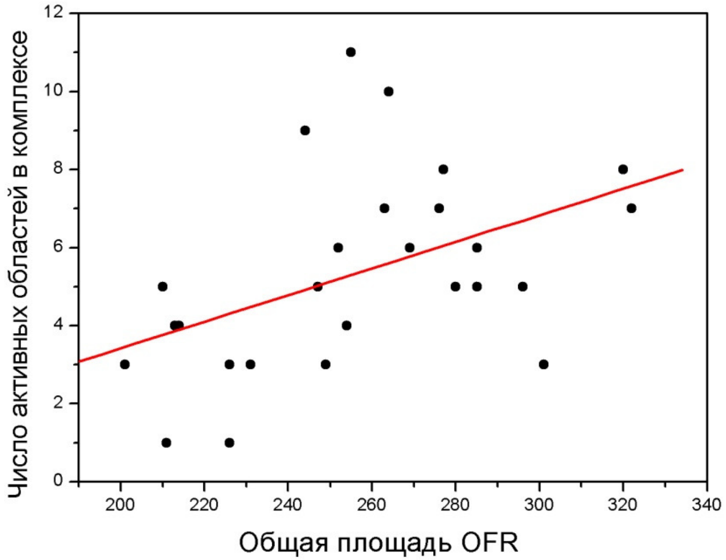


Complex 3 corresponds to the negative sector of the global field. It contains two open field regions connected with the pole. The total area of open field increases somewhat in the middle of the period. Active regions are few and small, and their appearance and disappearance does not affect the structure of the complex. Some large active regions appeared in the last two rotations (2009 and 2010), but they also had no appreciable effect on the structure of the complex.

Complex 4 corresponds to the positive sector of the global field. It consists of two or three small OFR surrounded at the photospheric level by an intricately shaped unipolar region of mainly positive sign with occasional small negative elements. Large active regions that appeared in rotations 2003 and 2004 did not significantly affect the structure of the complex. At the end of the interval (rotations 2007–2010), C4 contained virtually no active regions.

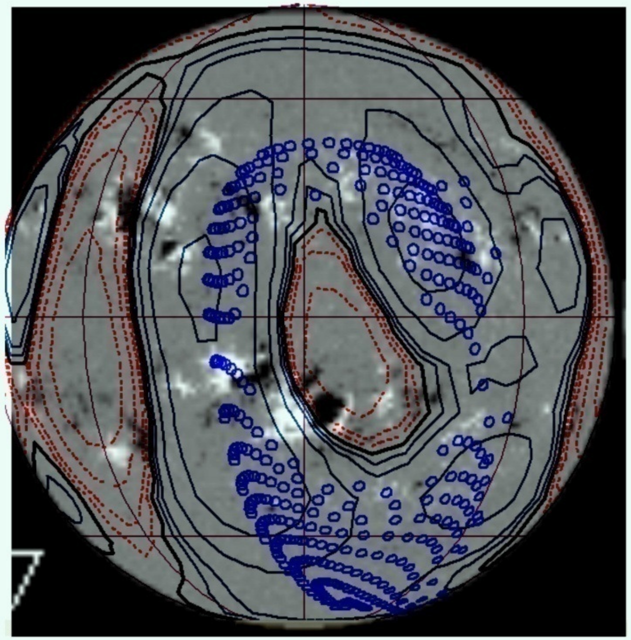
The relative areas of C3 and C4 were changing in anti-phase.??????????????





The number of active regions in a complex increases with the OFR area. Although the correlation coefficient is not high (0.39 ± 0.13 in the first period and 0.47 ± 0.15 in the second one), a positive tendency is evident.

Mutual location of OFR and active regions



The figure represents a map of the large-scale field observed on May 18, 2000. The small circles show the feet of open field lines (OFR). Superimposed on this map is the structure of the local magnetic fields observed by SOHO/MDI. It is seen that the largest active region at the disk center is located at the periphery (or even inside) the OFR. This area also hosts numerous less powerful active regions. A few more active regions are located on the neutral line of the large-scale field in the north-east quadrant.

To quantitatively estimate how close the sunspot groups are to the OFR, we analyzed the entire dataset. By “closed,” we mean groups whose centers are at a distance less than 10 heliographic radii from the OFR boundary.

First period, rotations 1954-1974 (September 1999 – December 2001)

Parameters	All active regions	Active regions in the vicinity of OFR	Active regions far from OFR
The sum of all AR areas	139342	105752/139342=0.759	33590/139342=0.241
The sum of AR areas >600 m.v.h.	68841/139342=0.494	55754/68841=0.810	13087/68841=0.190
The sum of AR areas <600 m.v.h.	70501/139342=0.506	49998/70501=0.709	20503/70501=0/291
The total number of AR	318	228/318=0.717	90/318=0.283
The number of AR with areas >600 m.v.h.	66	54/66=0.818	12/66=0.182
The number of AR with areas <600 m.v.h.	252	174./252=0.690	78/252=0.310

The second period, rotations 1997-2010 (November 2002 – December 2003)

Parameters	All active regions	Active regions in the vicinity of OFR	Active regions far from OFR
The sum of all AR areas	58992	41981/158992=0.71	17011/58992=0.29
The sum of AR areas >600 m.v.h.	24255/58992=0.41	21002/24255=0.86	3253/24255=0.14
The sum of AR areas <600 m.v.h.	34737/58992=0.59	20979/34737=0.60	13758/34737=0.40
The total number of AR	152	96=0.72	56=0.28
The number of AR with areas >600 m.v.h.	23	19/23=0.82	4/23=0.18
The number of AR with areas <600 m.v.h.	129	77/129=0.60	52/129=0.40

Both small and large sunspot groups are located in the vicinity of OFR; however, this effect is more pronounced if we consider large groups alone.

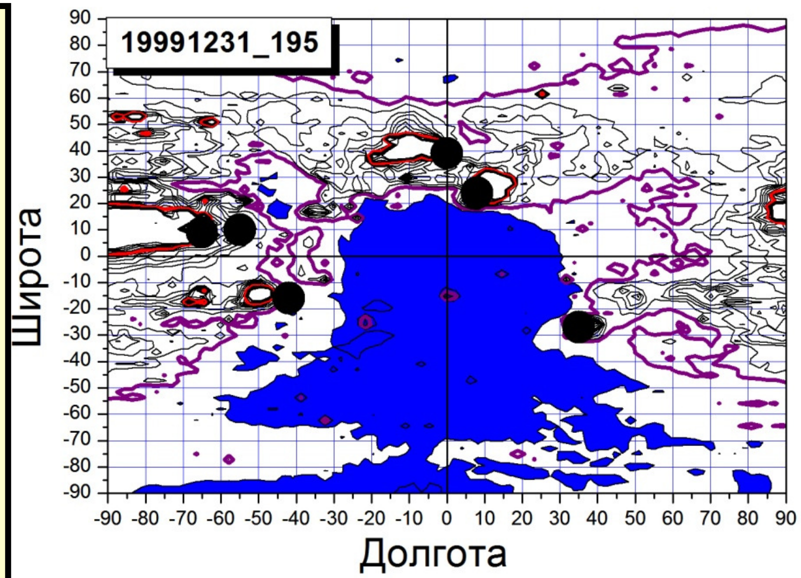
Analysis of photometric coronal holes

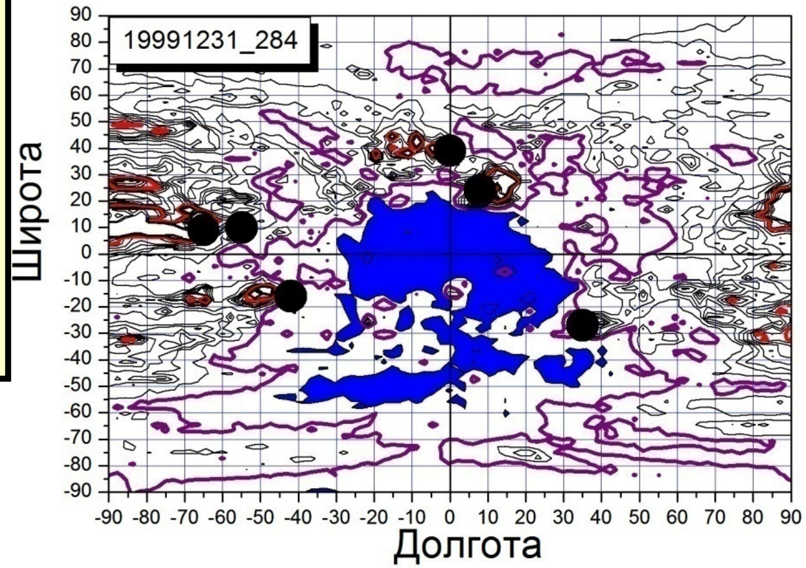
We have analyzed CH images taken in two lines (195 A and 284 A) on the day when the respective complexes were at the center of the visible disk. Each image was corrected for projection and was reconstructed in the form of a rectangular heliographic map.

An example of such maps is given on the next slide.

The brightness contour lines were drawn. The areas where the brightness is less than the mean brightness on a given day are colored blue. The contours of double mean brightness are shown with magenta lines, and the contours of tenfold mean brightness are red. The black circles denote sunspot groups.

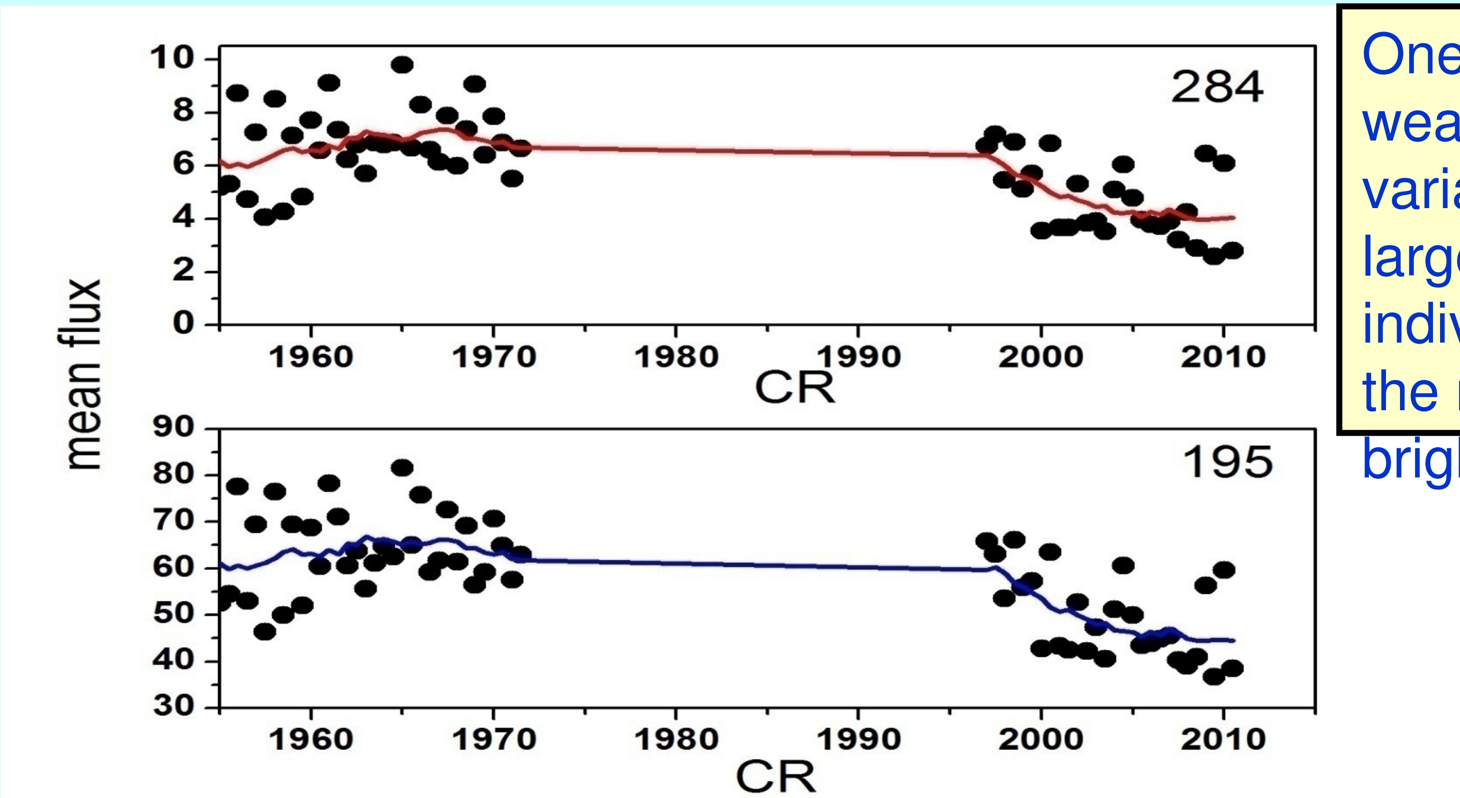
In this study, we have adopted as the CH photometric boundary the contour line of the disk mean brightness on the given day. One can see that transition between the photometric boundaries of CH and AR occurs between the contour lines of single and double mean brightness. In this case, a more precise identification of the boundary has little effect on the result.



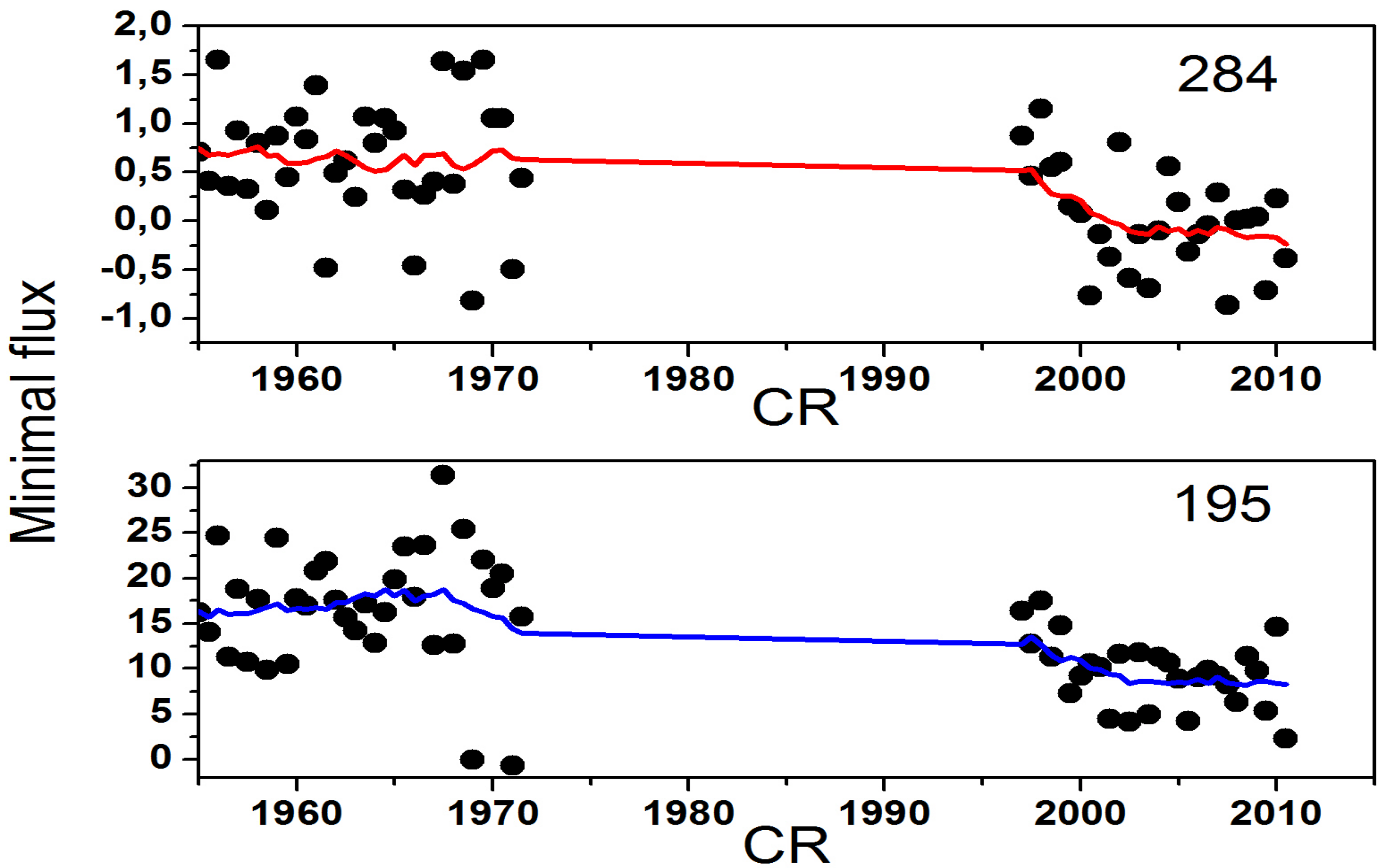


Despite the general similarity, the CH images taken in the two aforementioned lines are seen to differ significantly. CH in the 284 A line is smaller and has a much more indented contour.

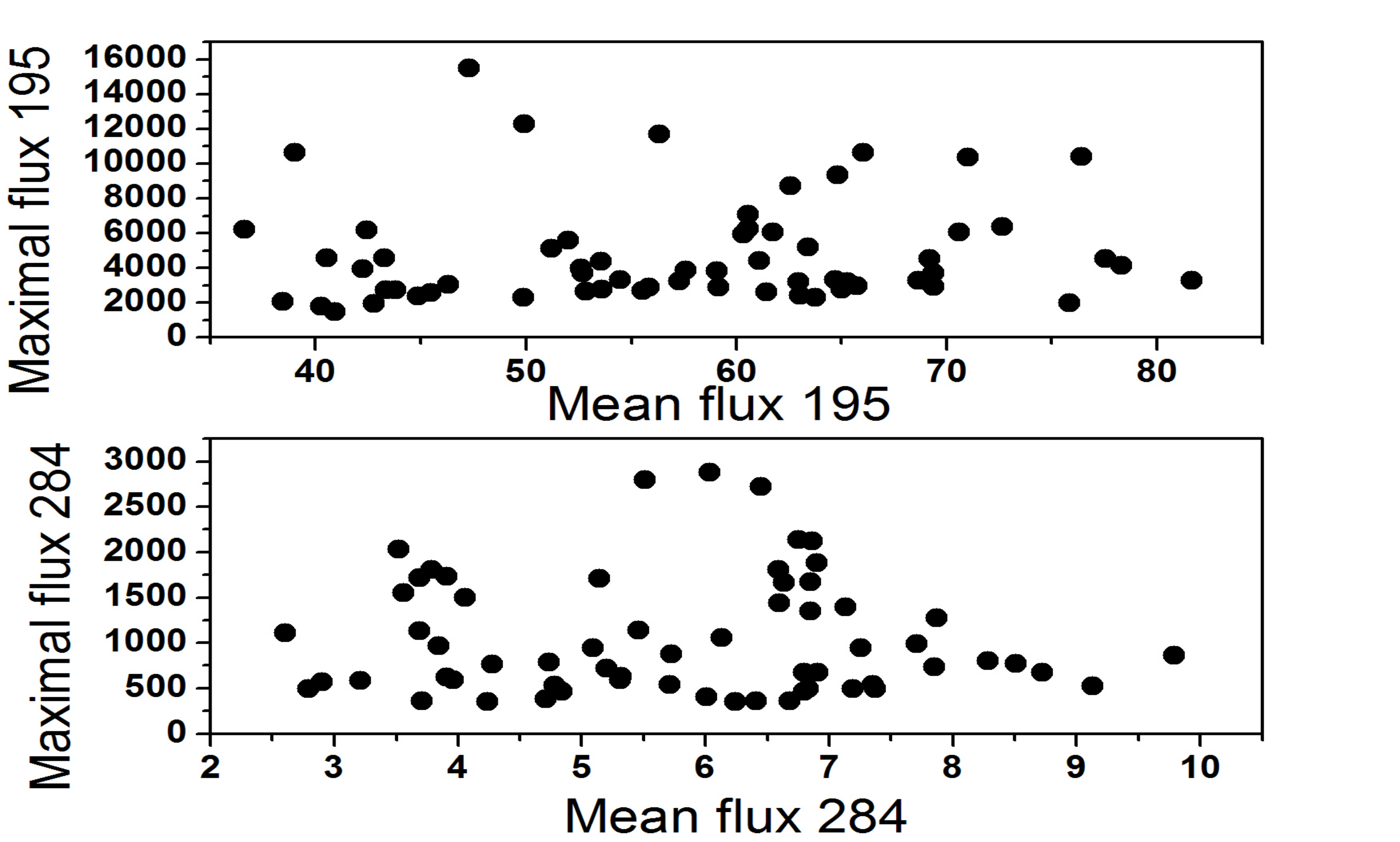
Since the CH boundary was identified based on the actual mean brightness over the disk, it was necessary to find out whether the latter was associated with the sunspot activity or varied independently of the cycle phase as shown earlier by Obridko and Shelting (2012). To do this, we found the minimum, maximum, and mean brightness for each image.



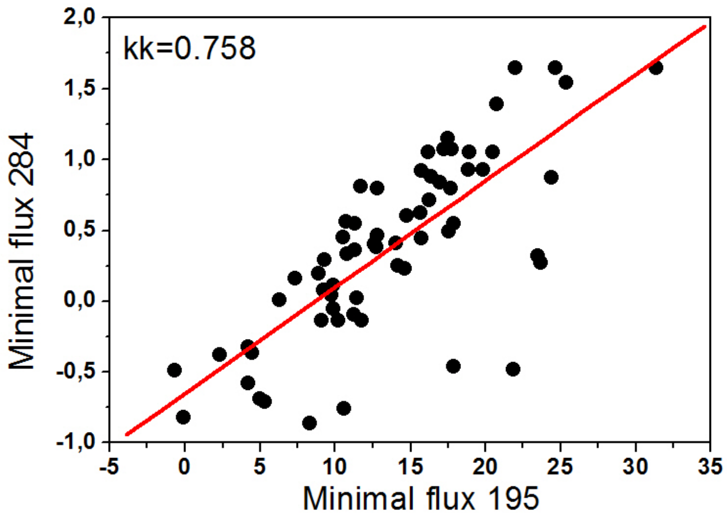
One can see a weak cycle variation and a large scatter of individual values of the mean brightness.

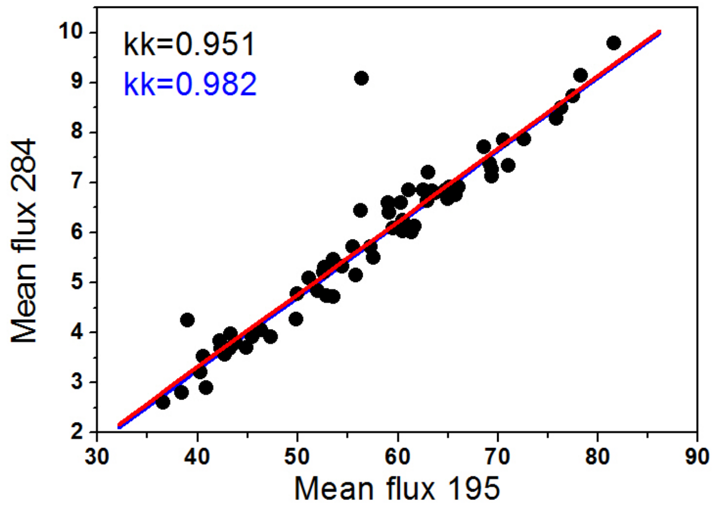


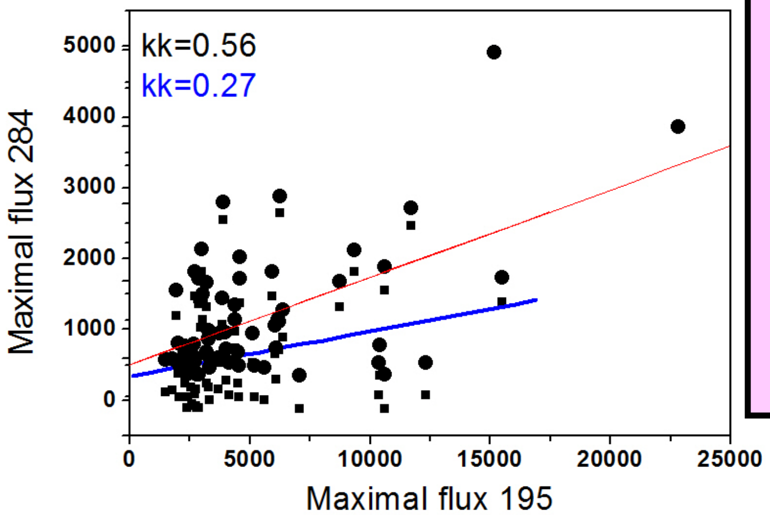
A similar cycle variation is observed in the minimal disk brightness.



On the other hand, no relationship is revealed between the mean and the maximum brightness.





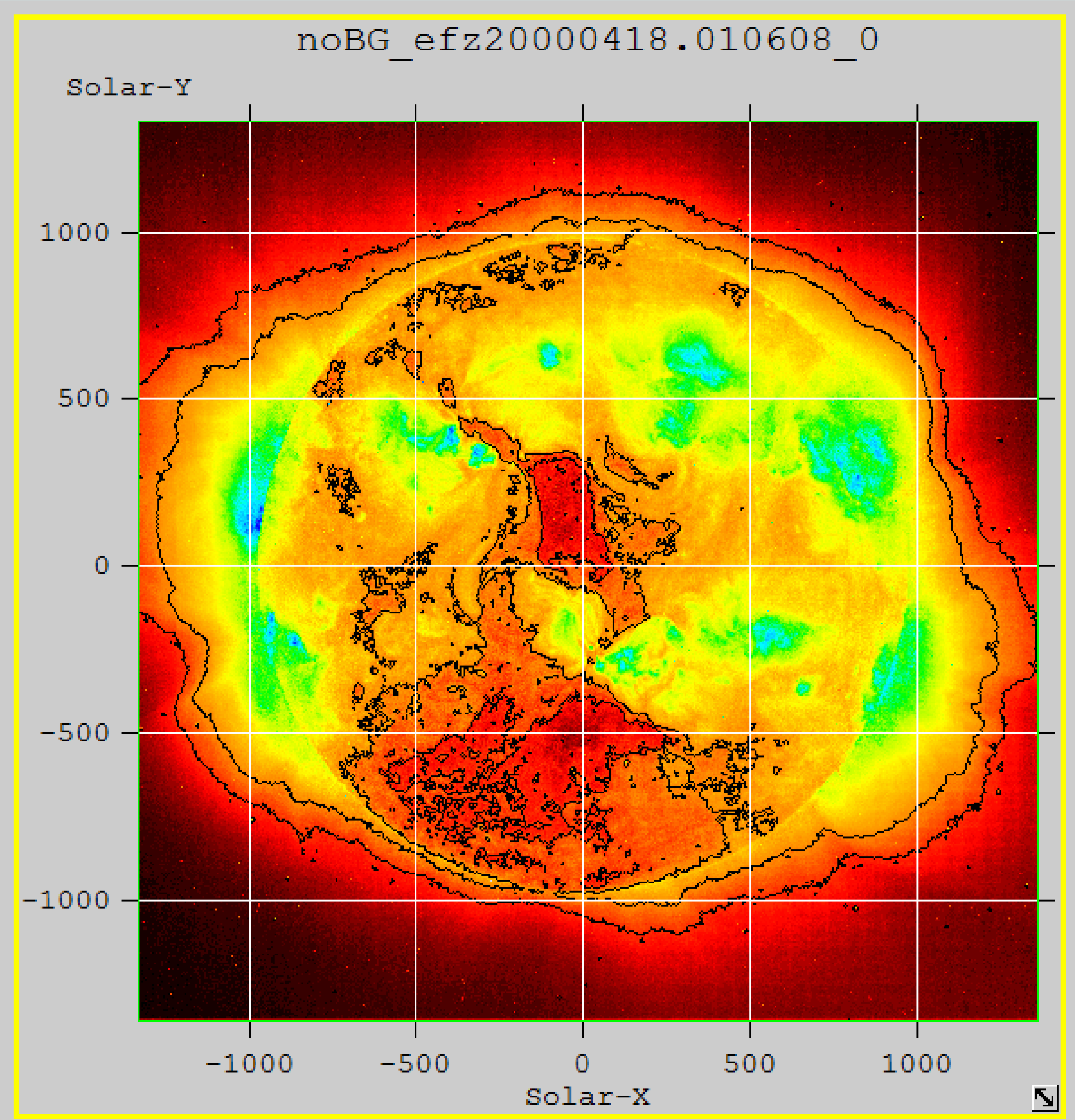


The red line was drawn through all points, and the blue one, through the same points except the images taken during flares.

The correlation is fairly good between the minimum brightness values in the two wavelengths and even better between the mean values, while the maximum values do not virtually correlate at all.

Comparison of photometric coronal holes with the locations and areas of sunspot groups

Unlike the previous case, we considered all sunspot groups observed on the day when CH was recorded at the center of the disk as part of the complex. Note that the analysis was made of the group current area on the day of observation rather than of its area at the peak of evolution.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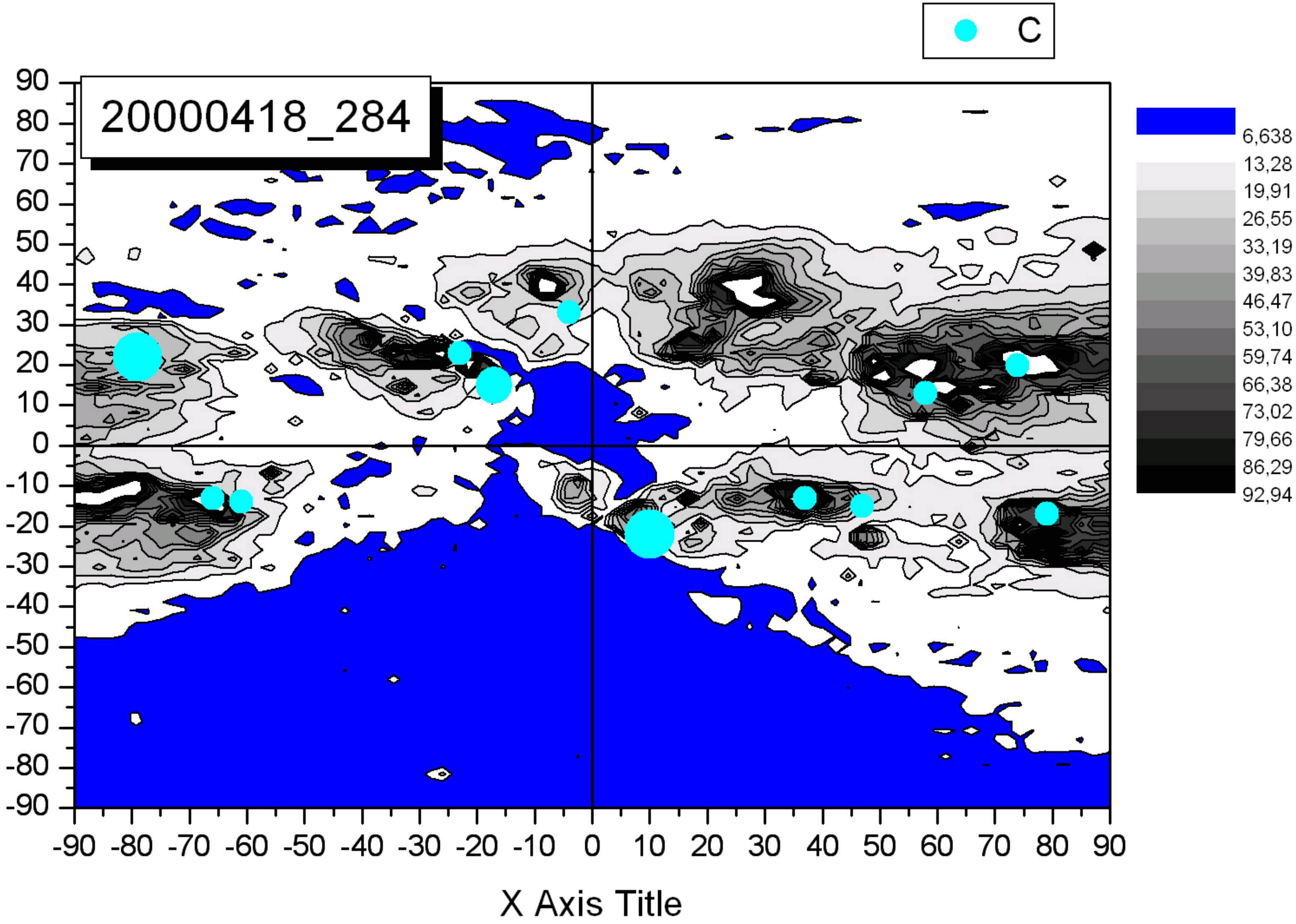

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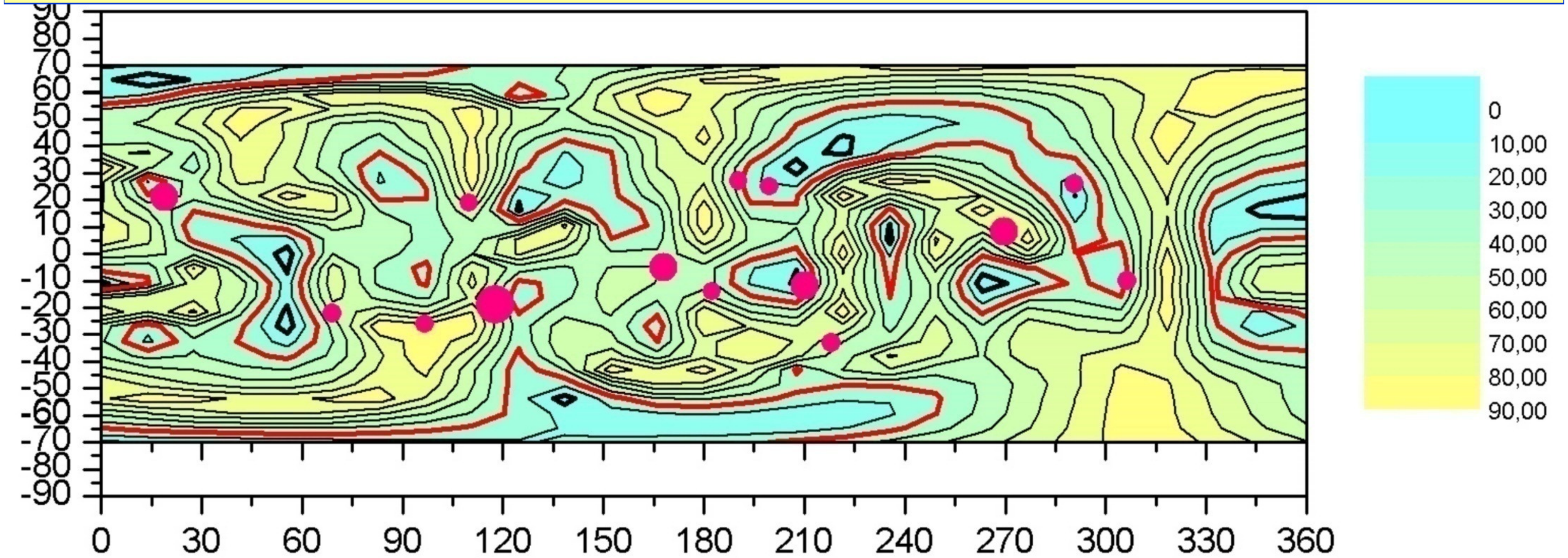
X Axis Title

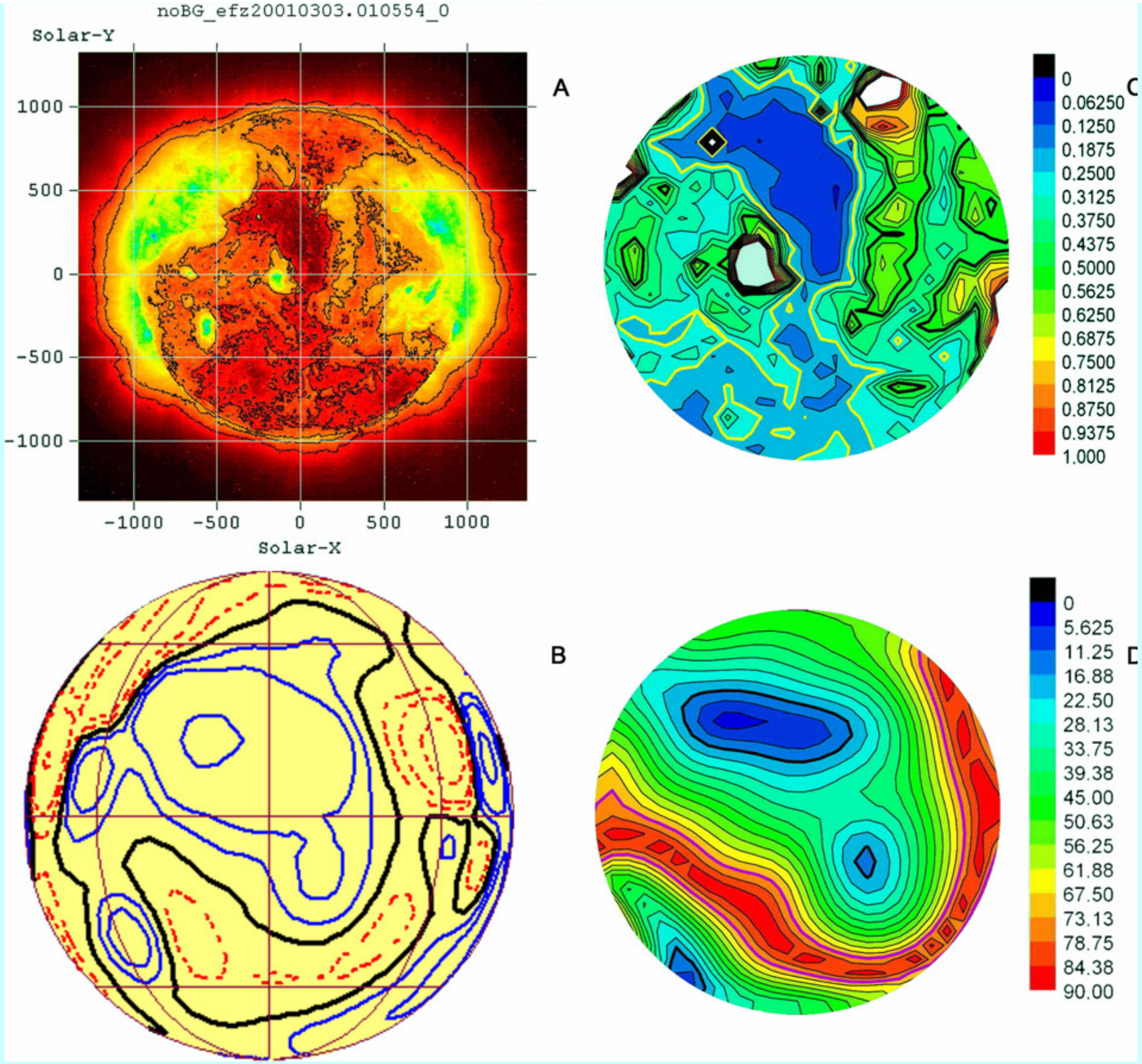
The location of sunspot groups with respect to CH

The first period: rotations 1954-1974 (September 1999 – December 2001)			
	All AR	AR in the vicinity of CH	AR far from CH
Total area	41804	26477/41804=0.633	
Total number of AR	284	186/284=0.655	
The second period: rotations 1997-2010 (November 2002–December 2003)			
Total area	21034	17049/21034=0.811	
Total number of AR	147	111/147=0.755	

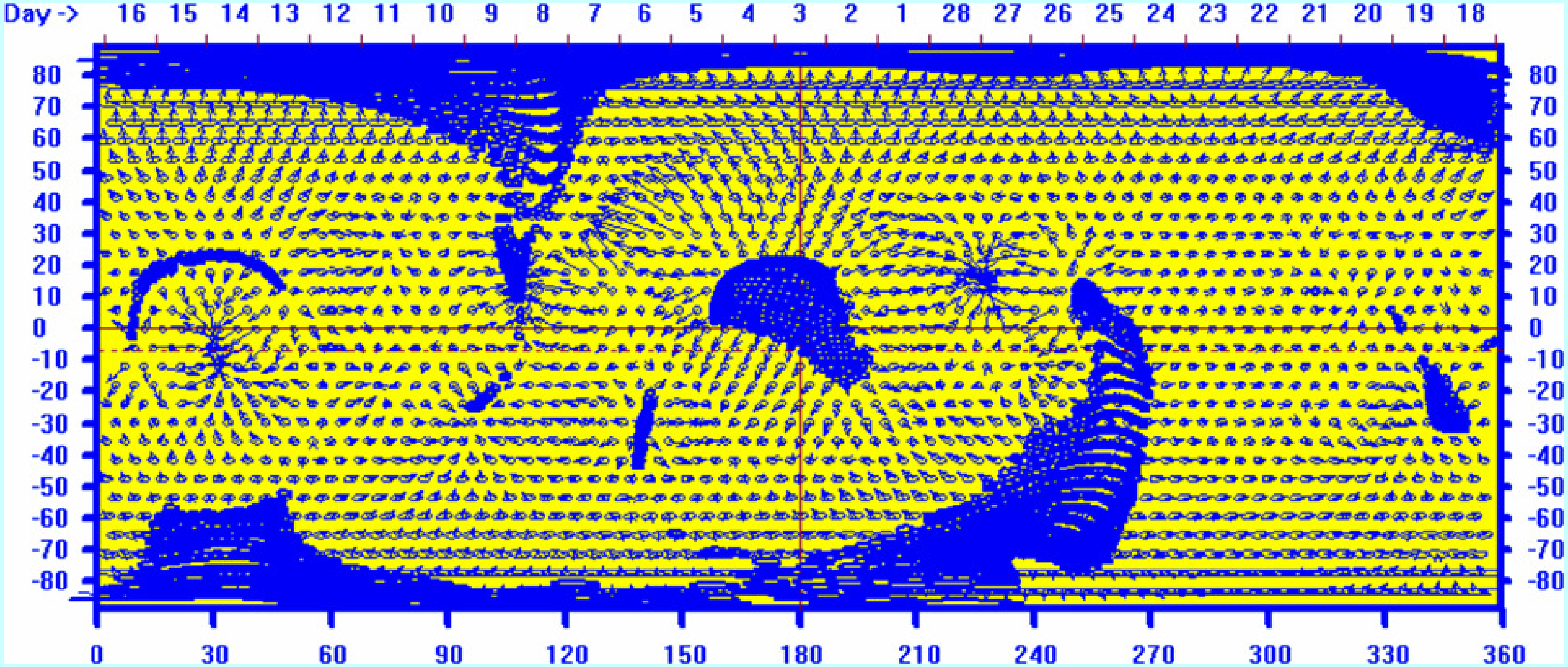
Coronal holes originate in OFR regions where the field lines are mainly radial. With distance from the region of strictly radial field, the force lines associated with the ambient photosphere become more and more inclined. The CH continues to exist until the inclination reaches 20˚, although its contrast decreases gradually. As a result, a feature appears that can be considered a sort of CH “penumbra”. Further, as the inclination reaches 50˚, the brightness of the CH environment becomes comparable to the brightness of the undisturbed chromosphere. The region of the field lines with inclination between 20˚and 50˚ is where the active regions that are conjugate to the CH are located (*Obridko and Shelting, 2011*).



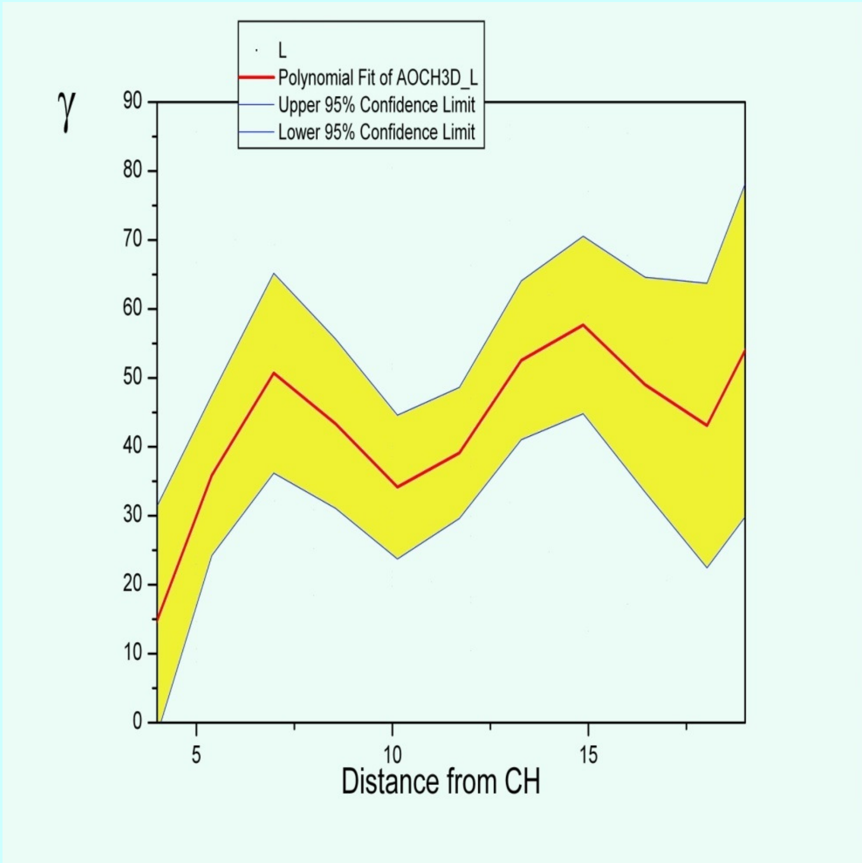
The figure shows as an example a synoptic map of the field line inclinations for rotation 1959. The color scale corresponds to inclinations from 0˚ to 90˚.The 10˚ contour is shown as a bold line and the 30˚ contour , with a red line. The circles represent sunspot groups, with the size of the circle corresponding approximately to the group area. Most of the circles are located within the 50˚ contour, and are mainly on the 30˚ contour.



Panel A displays the original SOHO/EIT; panel B shows the structure of the radial magnetic field at 1.1*R.* Pane C shows the brightness structure. The disks displayed in C and D correspond to the central disk of radius 0.6*R.* Panel D shows the departure of the field lines from the radial direction at 1.1*R in degrees; the thick black line corresponds to deviation < 20∘ from the radial* direction, and the yellow line to deviation < *75∘.*



Synoptic map of the transverse magnetic field for a single rotation with the coronal hole of 3 March 2001 at the center. The blue circles mark the open field regions


L
Polynomial Fit of AOCH3D_L
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Distance from CH

Relationship between the number of sunspot groups in the vicinity of CH and the area of the latter

In the first complex (18 points, 16 degrees of freedom), the correlation coefficient is -0.086+/- 0.081. The Student's T-test for the angular coefficient is 0.34549; i.e., the correlation is completely absent.

In the second complex (18 points, 16 degrees of freedom), the correlation coefficient is -0.599+/- 0.452. The Student's T-test for the angular coefficient is 2.989; i.e., the correlation is negative with a low correlation coefficient, but the tendency is well pronounced with reliability more than 99%.

In the third complex (14 points, 12 degrees of freedom), the correlation coefficient is -0.025+/-0.023. The Student's T-test for the angular coefficient is 0.345; i.e., the correlation is completely absent.

In the forth complex (13 points, 12 degrees of freedom), the correlation coefficient is -0.549+/-0.425. The Student's T-test for the angular coefficient is 3.831; i.e., we have negative correlation with a low, not very reliable correlation coefficient, but the tendency is well pronounced with reliability more than 99%.

In general, one can see a weakly pronounced negative correlation

If we compare the number of active regions and CH area within $\pm 40°$ from the visible disk center, we will see a situation quite different from the one observed when comparing sunspots with the open field regions (OFR) (see slide 16 above).

Instead of the previously observed weakly pronounced tendency of the number of sunspot groups to increase with growing OFR area, we have rather an uncertain pattern.

On the one hand, this may be due to different criteria used to select the sunspot groups. However, most likely, this is the result of different mechanisms of formation of OFR and CH. The open field regions are fully controlled by the underlying magnetic field, while an important role in the formation of CH belongs to the heating mechanisms. Thus, sunspot groups do not passively reside in the vicinity of coronal holes, but affect their brightness and photometric structure through the side heating. Active regions arise preferably in the vicinity of OFR and CH, but they decrease the CH area and displace its boundary through heating.

Discussion of results

Complexes of activity are not a random combination of a several active regions into a single feature with a common position on the disk and similar evolution for several solar rotations. They are an essential element in the overall scheme of large-scale organization of solar activity both at the spatial and at the long time scales. Their formation and evolution are controlled not only by local fields but also by global processes .

The mechanisms responsible for the global organization of solar activity are the large-scale solar dynamo and meridional flows.

Today it is clear that the second condition for the occurrence of coronal holes at mid latitudes, besides the open configuration of the global magnetic field, is the existence of active regions with a strong local field in their environment. The relation between CH and AR was established in the early work based on *Skylab* data (*Levine, 1977; Wang et al., 1988,* and Wang, Yoshimura, and Kundu, 1988). The appearance of the open field of CH is usually accompanied by the formation of two systems of closed field lines. Later on, it was shown (*Shibata, Yokoyama, and Shimojo, 1994; Mogilevsky, 1995*) that, sometimes, the change of the boundaries and energy balance in CH is largely due to sporadic and pulse-like fluxes of hot plasma (X-ray 'jets') and regular energy fluxes from the surrounding AR. The active regions in the vicinity of CH can be connected with the latter either dynamically or energetically (*Mogilevsky, Obridko, and Shilova, 1997; Obridko, 1998*).

General scheme of formation and evolution of a Global Complex

The magnetic field is generated at the base of the convection zone as a result of combined action of the toroidal magnetic field and differential rotation (Ω-dynamo). This field emerges from the tachocline mainly in the equatorial zone, possibly, in the form of separate flux tubes. Magnetic field in the emerging tube is mainly radial. However, the larger part of the bipolar active region has a transversal field. The field outside the active region is mainly transversal, too (*Obridko and Chertoprud, 2011; Hinode).* Therefore, it is more likely that the quadrupole (or bipolar) structure arises in immediate proximity to the surface. In particular, *Khlystova (2012*) has shown that the transversal velocity component is strong in the course of the emergence.

However, the central part of the tube remains radial and retains its connection with the underlying layers. Thus, the central part of the complex is the region of open field lines. At the same time, a dark X-ray or UV feature (i.e., a coronal hole) may arise in the vertical field owing to particularities of the coronal heating. At the periphery of this feature, where the field lines depart from the radial direction, active regions are formed. They, in turn, affect the open field region distorting its configuration. The rotation period of active regions somewhat differs from that of the underlying field. The surface fields rotate at Carrington velocity, while the rotation of the deep field is close to the solid-body rotation type with a period of about 27 days.

After several rotations, the active regions decay. Their influence on the deep field tube ceases gradually, and the open field configuration is restored. A new coronal hole appears *(Yazev and Pevtsov)*. However, it is not formed of the remnants of the active region, but is rather associated with the underlying field.


Thank You for attention !