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# COMPLEXES OF ACTIVITY ON THE SUN IN SOLAR CYCLE 21

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**Abstract.** The paper provides statistical data on solar activity complexes (ACs) observed in solar cycle 21. From the synoptic charts for the 1976–1986 sunspot activity, we have detected the regions where the sunspot generation was observed at least through three Carrington Rotations (CRs). These regions were identified as AC cores. We have compiled an AC catalogue. ACs are shown to evolve quasi-periodically, in pulses that are 15–20 rotations long. We have analyzed the North-South asymmetry in the AC location. In cycle 21, 90 % of the proton flares that affected the natural environment are shown to have occurred in ACs. We note a tendency for AC activity to decrease, as well as the manifestation of the Gnevyshev—Ohl rule in AC properties, in solar cycles 21–24.

**Keywords:** solar activity, activity complexes, flares, North-South asymmetry.

## INTRODUCTION

Activity complexes (ACs) on the Sun are traditionally of great interest as geoeffective structures generating the most powerful flares, including proton events [Howard, Swestka, 1977; Ogir, 1976; Bumba et al., 1986; Golovko, 1983, 2001]. Different authors called such formations centers of solar activity [Vitinsky, 1965] and even "nests" of sunspots [Castenmiller et al., 1986]. The concept of AC has changed over time — from large-scale magnetic structures, described by Bumba and Howard [1965] (they also proposed the term AC), to complex systems of numerous active regions (ARs), located along the solar parallel and encircling the Sun [Gaizauskas et al, 1983]. The terms AC and CAR (complex of active regions) are often considered as synonymous [Ishkov et al., 1988; Sattarov, 1989; Sattarov, Saidalieva, 1991; Mogilevsky, Shilova, 1998; Sattarov et al., 2001; Ryabov, Lukashuk, 2009]. V.N. Obridko in his monograph [Obridko, 1985] gives little attention to AC: he notes that this type of solar formations is poorly known. Later, the author proposed a new concept of the global activity complex [Obridko, Shelting, 2013; Obridko, Nagovitsyn, 2017] that describes structures related to powerful sunspots and extending from the deep layers of the convective zone [Kosovichev, Duvall, 2006; Ilonidis et al., 2011] to the corona. In general, the modern literature is dominated by the concept of AC as a large flare-active region or a system of several such ARs.

A slightly different approach is proposed in [Banin, Yazev, 1989, 1997]. As the key parameter of AC the authors took the lifetime of AR at least through two rotations in the same area of the solar surface in the Carrington coordinate system. This means that sunspots should be observed at least three times during three consecutive rotations. Since the lifetime of one sunspot group in most cases turns out to be several times shorter [Bray, Loughhead, 1967; Vitinsky et al., 1986], the presence of sunspots at the same place for several rotations implies that new magnetic flux portions emerge there one after another from under the photosphere as new ARs. Such areas of long-term sunspot generation with an empirically determined size of 20°×20° were originally called areas of long-term activity [Banin, Yazev, 1989], and later another term was proposed for them — AC cores [Yazev et al., 2011, Yazev , 2015]. This approach also uses the concept of AC branch — AR in a given Carrington rotation located nearby (at a distance of no more than 30°) the AC core, connected to AR, located in the AC core, by high coronal loops. The branch (individual AR) exists for a relatively short time as compared to the AC core, where ARs can alternate. The AC branch obeys differential rotation (unlike the AC core), gradually shifting in longitude in the Carrington coordinate system. The active regions, which are simultaneously located in the AC core and in the AC branch, form a complex of active regions (CAR) in this rotation. Thus, CAR within this approach is a one-time "cut" of AC — a description of its state at a given time regardless of its long-term evolution. In the next rotation, this branch is already absent, but the AC core can continue to exist as a new AR emerging at the same place. In this case, the general magnetic structure of AC can persist, slowly evolving through several rotations [Yazev, 2015].

A series of papers by authors belonging to the Irkutsk school is devoted to studying ACs understood in this sense (for example [Banin, 1983; Banin et al., 1988; Yazev et al., 2011; Yazev, 2015; Isaeva et al., 2018, 2020]. These papers describe the phenomenology of AC for the photosphere and chromosphere, using several pronounced ACs from observations in the Hα line as an example [Banin, 1983; Komarova et al., 2004]. Besides, the statistics of AC manifestations in 1980–2020 over three and a half solar cycles has been examined [Yazev et al., 2011; Isaeva et al., 2018]. The choice of this interval is due to the fact that in 1980 the Full Disk Chromospheric Telescope of the Baikal Astrophysical Observatory of the Institute of Solar-Terrestrial Physics SB RAS (at that time SibIZMIR SB AS USSR) was commissioned [Banin et al., 1982]. This instrument for observing the full solar disk in the Hα line with a high resolution made it possible to analyze photospheric and chromospheric manifestations of ACs on the Sun, using its synchronous data, as well as to plan and monitor ACs [Borovik et al., 2019]. As a result, the analysis of AC evolution in solar cycle 21 was limited to the period 1980–1986 [Yazev, 2010a], and the AC dynamics during growth phases and the beginning of the maximum of solar cycle 21 (1976–1979) remained unknown.

This work aims to fill this gap. We study ACs developed in the first half of solar cycle 21 (1976–1979 inclusive). This allows us to update the available data, to figure out how AC evolved throughout solar cycle 21, and also to compare our findings with the previously obtained data on ACs in cycles 22–24.

## METHOD AND DATA

To identify ACs that developed in the first half of cycle 21, we have constructed synoptic charts of the solar surface in Carrington heliographic coordinates (CR 1637–1689, January 1976 – December 1979). Similar charts starting from CR 1690 (January 1980) were constructed and analyzed in other works [Yazev, 2010b].

All groups of sunspots at the stage of their maximum development are marked on the charts according to Solar Geophysical Data for the respective four years. We used sketches of the sunspot groups and tabular data, including coordinates of the sunspot groups, which are numbered according to the NOAA nomenclature.

Then we applied the following algorithm. On the synoptic charts, 20°×20° areas stood out, within which sunspot activity was observed for at least three rotations. Such areas were identified as AC cores. During this period, a catalog of AC cores was compiled. It contains the AC core number (separate numbering for objects located in the northern and southern hemispheres of the Sun); the number of AR located in a given rotation within an AC core according to the NOAA nomenclature; heliographic Carrington coordinates of the AC core center; the power index *P* of AC core in a given rotation (the *P* index is assigned to each AR during its maximum development; the scale of *P* values is described in Table 1 [Yazev, 2015]); numbers of ARs forming AC branches in a given rotation; the total number of ARs (in cores and branches) in AC in a given rotation. A fragment of the catalog is given in Table 2.

This catalog allowed us to update the data on ACs in solar cycle 21, previously studied for the second half of this cycle [Yazev, 2010a, b; Yazev et al., 2011], as well as to analyze the development of AC in the entire cycle in comparison with other cycles. We present the results reflecting the dynamics of the special AR population on the Sun, unlike the entire set of sunspot groups (see, e.g., [Wang, Sheeley, 1989] also dealing with solar cycle 21) in the next section.

## SIGNATURES OF ACTIVITY COMPLEXES IN SOLAR CYCLE 21

The development of ACs in cycle 21 (Figure 1) began in CR 1648 when the first AC of this cycle emerged in the northern hemisphere. This happened six rotations after the start of the cycle (CR 1642). Three rotations after activation of AC in the northern hemisphere, the first AC also emerged in the southern hemisphere.

Table 1

Power index *P* of AC cores

| Importance | Description of sunspots in AC core | Analogue of the Zurich classification of sunspot groups |
|---|---|---|
| 0.5 | One or two groups of pores without bipolar structure | A, B or A+A |
| 1 | One sunspot group including a spot with penumbra, or three pore groups | C, or A+A+A, or B+B |
| 1.5 | Sunspot group with two or more sunspots with penumbra, or with one large sunspot, or two small groups | C+(A or B) or E,<br>or C+C,<br>or J, or H |
| 2 | A large group with a large number of sunspots and pores, including large sunspots, or two sunspot groups | E+(B or C),<br>either G+(B or C) |
| 2.5 | A large group of sunspots (area more than 1000 ppm), extent >20°, or two large sunspot groups | F or E+D |
| 3 | Extremely large sunspot group (area over 2000 ppm), or a large sunspot group with satellite groups next to it | F, extent >20° |

Table 2

Fragment of the AC catalog in solar cycle 21

| AC core number | Rotation number | AR number in AC core | Carrington coordinates of AC core | | *P* | Number of AR — AC branch | AR number in AC |
|---|---|---|---|---|---|---|---|
| | | | Longitude | Latitude | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 21N01 | 1648 | 733 | 155 | +12 | 0.5 | | 1 |
| | 1649 | 738 | | | 1 | | 1 |
| | 1650 | 744 | | | 1 | | 1 |
| | 1651 | 754 | | | 1 | 755<br>758 | 3 |
| | | | | | | | |

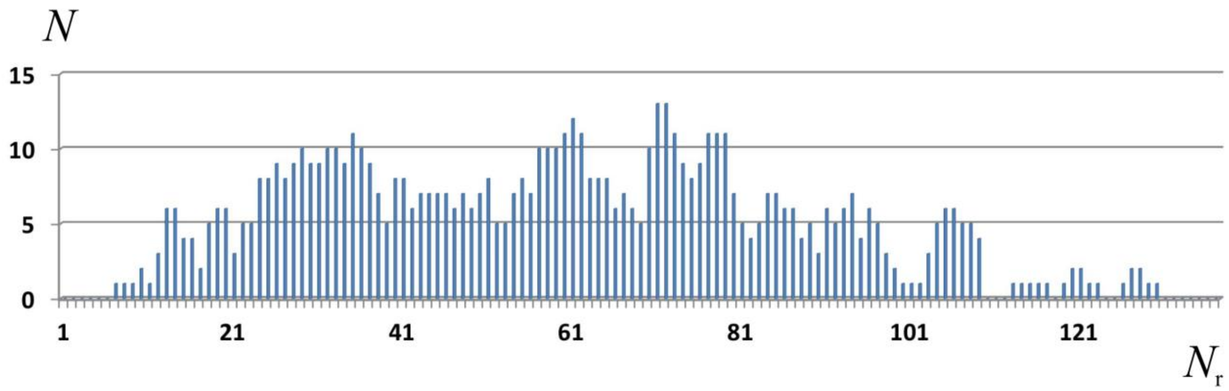


*Figure 1*. Variations in the number of AC cores *N* in solar cycle 21. Along the X-axis are numbers of Carrington rotations $N_r$ from the beginning of the cycle (CR 1642)

The last AC of cycle 21 in the northern hemisphere disappeared in CR 1769; in the southern one, in CR 1771. Thus, for the northern and southern hemispheres of the Sun, the cycle duration, in terms of the AC indices, proved to be almost the same, with a slight shift by 2–3 rotations (later in the southern hemisphere).

The total number of AC cores in this cycle was 133 (61 in the northern hemisphere, 72 in the southern one). Comparative data on cycles 21–24 is given in Table 3; data on cycles 22–24 is from [Yazev et al., 2011; Isaeva et al., 2020]. The alternation of higher and lower values of the number of AC cores is presumably associated with the manifestation of the Gnevyshev—Ohl rule. The small statistics do not yet allow us to draw deeper conclusions.

Figure 1 shows that the number of ACs is modulated by the general dynamics of the 11-year cycle. This is natural since ARs included in AC constitute a part of the general population of sunspot groups. During the cycle, quasi-periodic variations in the number of AC cores with a characteristic quasi-period of ~15 rotations are observed, which for the second half of cycle 21 has been revealed in early works [Banin, Yazev, 1989, 1997].

Table 3

AC cores in cycles 21–24

| Cycle number | Northern hemisphere | Southern hemisphere | In total |
|---|---|---|---|
| 21 | 61 | 72 | 133 |
| 22 | 52 | 52 | 104 |
| 23 | 69 | 77 | 146 |
| 24 | 64 | 50 | 114 |

Figure 2 illustrates the evolution of AC separately for the northern and southern hemispheres (for clarity, negative values are assigned to the number of AC cores in the southern hemisphere).

A tendency towards anticorrelation of AC development in the northern and southern hemispheres is clearly seen: at separate time intervals, as the number of ACs in one hemisphere increases, it decreases in the other. This peculiarity of the AC development was first noted in [Banin, Yazev, 1989] for the second half of cycle 21. A similar tendency is observed in the first half of the cycle under study.

It is convenient to describe the North-South asymmetry in the development of activity, using the asymmetry factor [Olemskoy, Kitchatinov, 2013; Kitchatinov, Khlystova, 2014] $K=(N_n-N_s)/(N_n+N_s)$, calculated for each Carrington rotation. At maximum asymmetry (no ACs in one of the hemispheres), $K$=1 or $K$=–1. If the number of northern and southern AC cores is equal, $K$=0, with ACs dominating in one of the hemispheres $|K| = 0 \div 1$ (Figure 3).

It can be seen that $K$ quasi-periodically changed sign — the AC cores prevailed alternately in the northern and southern hemispheres.

Let us turn to the integral properties of ACs in cycle 21. Since in previous works these properties have been determined for cycles 22, 23 [Yazev et al., 2011] and partly for 24 [Yazev, 2015; Isaeva et al., 2020], it makes

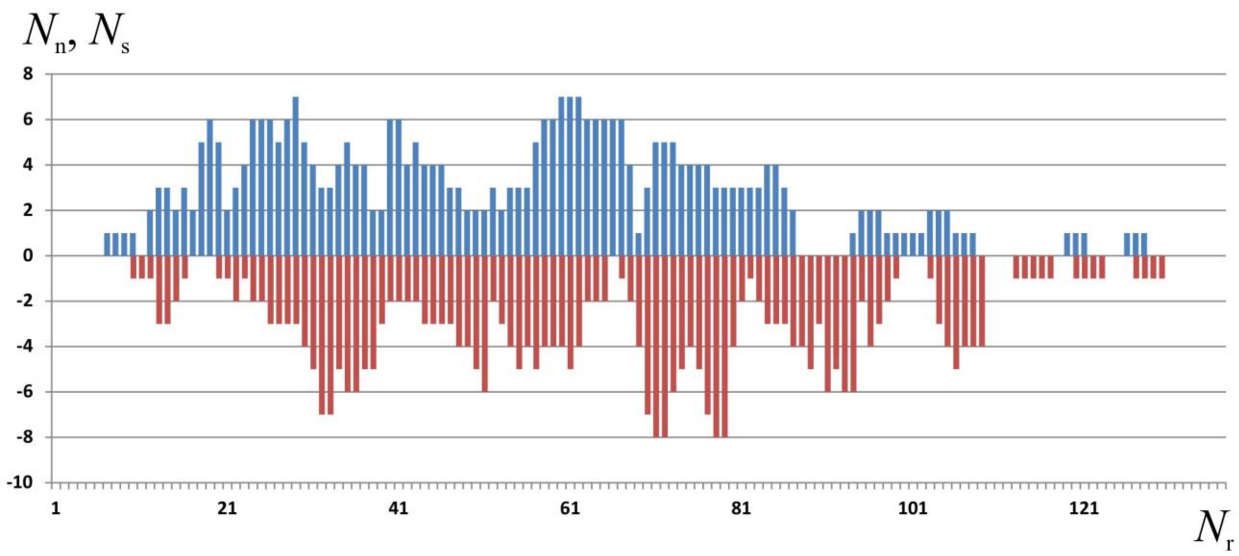


*Figure 2.* The number of AC cores in the northern $N_n$ and southern $N_s$ hemispheres of the Sun in cycle 21

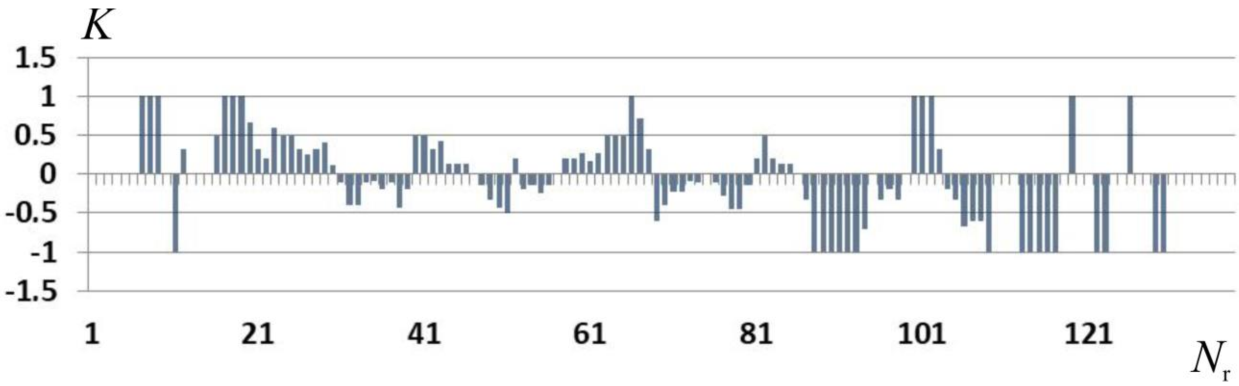


*Figure 3.* Variations in the asymmetry factor of the number of AC cores in cycle 21

sense to compare these cycles. The AC characteristics for cycle 21, determined using data from the new catalog, are listed in the first row of Table 4. The parameters of cycles 22 and 23 are from [Yazev et al., 2011; Isaeva et al., 2020]; those of cycle 24 are from the author's catalog of ACs, completed in 2020 after the end of the cycle. Thus, for the first time we have got a chance to compare four cycles, using the approach in hand (see Table 4).

In Table 4, columns give the following parameters: 2 – cycle duration in Carrington rotations; 3 – the number of rotations in which at least one AC core was observed; 4 – average number of AC cores per rotation; 5 – the mean specific power of AC core (total power *P* of AC cores in a given rotation, referred to the number *n* of AC cores in this rotation); 6 – the integral power *P* of AC cores in the cycle, summed over all rotations; 7 – mean power of AC cores per rotation. The average number of AC cores observed during one rotation was maximum (5.89) in solar cycle 21 under study. The mean specific power of AC core in rotation decreases monotonically from cycle to cycle. When calculating this parameter, we took into account only those rotations in which at least one AC core was seen on the solar disk. This was not always the case: in cycle 21, 19 "zero" (without AC cores) rotations of 137 were noted; in cycle 22, 29 of 130; in cycle 23, 44 of 168; in cycle 24, 39 of 146. At the beginning of the cycle, the number of zero rotations was respectively 6 in cycles and 22, 14 at the beginning 21 of cycle 23,

Table 4

Parameters of AC cores in solar cycles 22–24

| Cycle number | Number of analyzed rotations in a cycle | Number of rotations with AC cores | Average number of AC cores per rotation | Mean specific AC core power per rotation | Total AC core power per cycle | Mean AC core power per rotation |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 21 | 137 | 118 | 5.89 | 1.18 | 873 | 7.53 |
| 22 | 130 | 101 | 4.31 | 1.11 | 613 | 6.07 |
| 23 | 168 | 124 | 4.49 | 1.09 | 866 | 6.98 |
| 24 | 146 | 107 | 5.27 | 1.06 | 583 | 5.44 |

and 13 at the beginning of cycle 24. Thus, compared to cycles 21 and 22, the first AC in cycles 23 and 24 appeared with a noticeable delay relative to the beginning of the cycle, determined by the smoothed curve of monthly mean Wolf numbers [Obridko, Nagovitsyn, 2017].

Let us note the observed tendency for the integral power of AC cores to decrease. If we suppose that the Gnevyshev—Ohl rule manifests itself in AC power, it is worth to compare parameters not of neighboring cycles, but of neighboring even and odd ones. In both pairs of cycles 21–23 and 22–24, there is a tendency for the total AC power to decrease in the cycles. Accordingly, the mean AC power per rotation decreases. This parameter was the highest (7.53) in cycle 21, the lowest (5.44) in cycle 24.

Also noteworthy is the phenomenological property of ARs formed in AC cores. In cycle 21, the location of two (sometimes more) ARs was repeatedly observed at roughly the same longitude, but at different latitudes in the same hemisphere, spaced 5°–10° apart. Such cases prevailed in AC cores (less often in AC branches) and were observed (sometimes in different rotations) in 44 AC cores of 123 (36 %) during cycle 21.

Figure 4 presents a histogram of AC cores in cycle 21 in terms of the lifespan *T*, expressed in Carrington rotations. According to the definition of AC core, *T* cannot be less than three rotations. Similar estimates have been made for AC cores in cycles 22–24 [Yazev, 2010b; Isaeva et al., 2020], but only in cycle 21 the number of “four-rotation” AC cores exceeds the number of “three-rotation” ones – in cycles 22–24 the latter turn out to be much larger.

Table 5 presents data on the connection between AC cores in cycle 21 and the most powerful proton flares, which in Earth's orbit generated >10 MeV particle fluxes exceeding 10 $cm^{-2}s^{-1}$. A catalog of such events is available on the website [https://umbra.nascom.nasa.gov/SEP]. According to data from Table 5, 47 of 52 similar flares (90 %) occurred in ACs: 41 in ARs located in AC cores, 6 in ARs that are AC branches. The same value for cycle 24 is 82 % [Isaeva et al., 2018].

## CONCLUSION

We have determined characteristics of ACs that were identified within the approach developed by the Irkutsk school. The AC statistics increased from three to

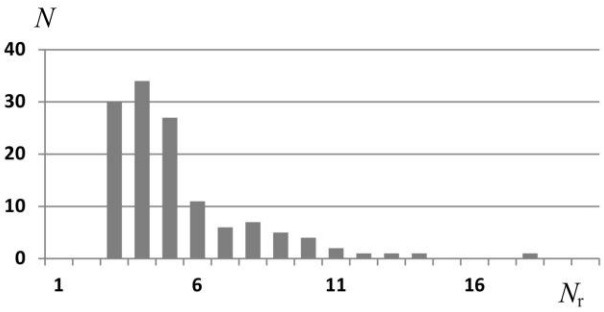


*Figure 4.* Distribution of AC cores in cycle 21 by their lifespan, expressed in Carrington rotations. Along the Y-axis is the number of cases *N*

Table 5

Parameters of AC cores in solar cycles 22–24

| | In total | In AC cores | In AC branches | Outside AC |
|---|---|---|---|---|
| Northern hemisphere | 31 | 23 | 4 | 4 |
| Southern hemisphere | 21 | 18 | 2 | 1 |
| Total | 52 | 41 | 6 | 5 |

four analyzed solar cycles: data on cycle 21 was added, AC parameters in cycle 21 were compared with those in cycles 22–24.

In general (in the first approximation), we can state that the characteristics of ACs in all the four cycles are similar. During a cycle, approximately 50–70 AC cores appear in each hemisphere.

ACs occur in pulses: the number of AC cores increases and then decreases, after which a new pulse is observed. The duration of each pulse is 15–20 Carrington rotations; 5–6 such pulses are observed in each hemisphere during a cycle. Taking into account the time shift (manifestation of the North-South asymmetry) characteristic of all the cycles under study, the total pulses of AC development on the Sun turn out to be somewhat longer (~20–25 rotations), which is likely a cause of the known quasi-biennial variations in solar activity [Vitinsky et al., 1986; Obridko, Nagovitsyn, 2017]. The data on solar cycle 21 allowed us to confirm the earlier conclusion that it is precisely the AC cores which is the main location of strong proton flares accompanied by energetic proton ejections. Statistics on the entire period of observation of such flares from GOES satellites (1976–2021) suggest that ACs are responsible for 80–90 % of all such events.

A closer look can reveal some differences in the behavior of ACs from cycle to cycle. The lifespan of cores is gradually decreasing: there are more and more short-lived ACs existing for no more than three rotations and the number of long-lived structures decreases. Later (with respect to the beginning of the cycle, determined from monthly mean Wolf numbers), the first ACs appear after 6 rotations in cycles 21–22; after 13–14 rotations, in cycles 23–24. Fluctuating, the AC core power decreases — the complex parameter that takes into account both the area of AR in the AC core and the number of ARs observed per rotation in the AC core. The mean specific power of AC core in rotation gradually decreases. Apparently, considering that the largest ARs are observed in ACs, this fact at least does not contradict the peculiarity noted in cycle 24 — a decrease in the number of large sunspot groups distinguished for a large magnetic flux [Penn, Livingston, 2010]. Unlike cycle 21, in cycle 24 there were significantly fewer AC cores with *P*=2.5 and *P*=3. Cycle 21 exhibited the largest average number of AC cores observed simultaneously during one rotation; in subsequent cycles, this parameter was lower.

These peculiarities of the dynamics of AC activity from cycle to cycle confirm the thesis of V.N. Ishkov that the Sun is entering the era of low cycles [Ishkov, 2018]. Since ARs developing as part of AC are an important part of the entire population of sunspot groups, their dynamics largely determines sunspot activity of the Sun as a whole.

It is noteworthy that higher and lower values of some AC parameters alternate, which may be associated with the manifestation of the Gnevyshev—Ohl rule, generally derived from Wolf numbers [Vitinsky et al., 1986]. Yazev [2015] has shown that Wolf numbers and AC power correlate well; therefore, this hypothesis seems to us reasonable.

Note (and we are clearly aware of this) that the statistics are extremely small (only four cycles were studied using a common methodology) and it would be incorrect to determine long-term trends based on the analysis of cycle-to-cycle variations. If the typical properties of ACs are confidently confirmed by analyzing the data for cycle 21, we can only speak with great caution about the long-term tendencies towards their cycle-to-cycle variations.

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