CRITICAL EVALUATION OF ESTABLISHED PARADIGMS ON THE MORPHOLOGY OF SUNSPOT GROUPS

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Abstract. A brief review of the most complex and interesting magnetic configurations of active regions is presented, the purpose of which is to draw the community's attention to the issue of significant systematic deviations from the traditional paradigm about the active region (AR) as a pop-up bipolar magnetic tube. The observations suggest the following. Large spots (including unipolar spots), as stable formations, appear to have deep roots and serve as channels that facilitate the escape of magnetic structures to the surface. Apparently, convective flows beneath the photosphere on a regular basis create a configuration different in principle from the classical bipolar configuration: a vertical tourniquet-spot and a system of chaotically entangled loops in the vicinity. It was in such magnetic structures that the most powerful flares of the 23rd, 24th, and 25th cycles occurred. Such magnetic structures - a tourniquet-stain plus a tangle of loops - according to the Crimean Magneto-Morphological Classification (CMC) belong to the highest complexity class, B3. Class B3 groups are responsible for extreme flash activity [Abramenko, 2021]. Apparently, everything that does not fit within the classical empirical laws on the structure of ARs is itself ordered, and carries the maximum load on the magnetic and flare activity of the Sun.

Keywords: *Sun, magnetic fields, active regions, photosphere, flares*

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1. INTRODUCTION

The physical basis for the classification of sunspot groups has emerged since Hale's discovery of magnetic fields in them [Hale et al., 1919; Hale and Nicholson, 1925].

However, only the phenomenological model of the solar dynamo proposed by Babcock [Babcock, 1961] and Leighton [Leighton, 1969] allowed us to give a physical explanation of the observed properties of sunspot groups, which, at first sight, agree well with the ideas of the dynamo theory. These properties as empirical laws of active regions (ARs) are well represented in the current literature in the review by van Driel-Geszteleyi and Green [2016], in particular, individual active regions are mostly bipolar and obey Hale's law of polarities, the tilt of the group axis obeys Joy's law, there is spot dominance of the leading polarity, and so on. The very discovery of the dynamo process and the realization of its role in solar physics was so overwhelming that there was a temptation to explain all the properties of sunspot groups and solar magnetism in general within the dynamo theory. In the literature appeared formulations: "The laws of sunspot polarities ... apply (with minor exceptions) to all sunspot groups, which are essentially *bipolar*" [Bray and Lawhead, 1967]. The monograph by Vitinsky, Kopetsky, and Kuklin [1986] says: "In the vast majority of cases, the polarities of the magnetic field of the head and tail parts are clearly distinguished, and the group has a clearly pronounced *bipolar* structure". Even in modern textbook monographs, e.g., Lang [2009], there are statements, "The magnetized atmosphere in, around, and above the bipolar spot groups is called the active region ... The number of active regions, with their bipolar spots ... varies according to the solar cycle." In such formulations, the bipolar structure of a spot group appears as its inherent attribute, and the active region itself is treated unambiguously as a bipolar.

However, in recent decades and years, especially with the development of solar flare and coronal mass ejection forecasting, there has been interest in very complex spot groups, in δ-structures, and in general in ARs that deviate from the classical empirical laws of dynamo theory, see, e.g., Bai [1988], Chen et al. [2011] and the reviews by Toriumi and Wang [2019], van Driel-Geszteleyi and Green [2016].

In particular, the Crimean Astrophysical Observatory developed [Abramenko et al., 2018; Abramenko, 2021] a magneto-morphological classification (MMC) of active regions based on observational data on the sub-photospheric distortion of the regular toroidal flow under the action of turbulence in the convective zone. According to this classification, bipolar ARs obeying the laws of the mean-field dynamo theory (Hale's law of polarities, Joy's law of the preferential inclination of the AR axis, the rule of dominance of the leading spot compared to the tail spot) belong to the class of regular ARs and are subdivided into two subclasses: A1 - regular ARs without peculiarities (i.e., coherent bundles of loops, which can be regarded as the resurfacing of a single magnetic loop-like structure obeying empirical laws and undergoing the minimum impact of sub-photospheric turbulence). A2 - regular ARs with a small δ-structure, whose spots are significantly smaller than the main AR spots. We consider the appearance of any δ-structure as an intrusion of a new flow, independent of the pre-existing one, and, therefore, as an interference of sub-photospheric mixing of flows. Therefore, A2-regions can be considered as structures with a small, but still more noticeable than in the case of A1-regions, interference of sub-photospheric turbulence. Unipolar spots are allocated to a special class U. All other AOs constitute the class of irregular AOs, class B, and are also subdivided into subclasses. B1 - bipolar regions that violate at least one of the above empirical laws; considered as single tubes on which turbulence has affected only in changing either the orientation or the inclination of the tube. B2 - multipolar ARs consisting of two or more co-directed bipoles, and also strong δ-structures; considered as the result of fragmentation and/or strong torsion of a single toroidal tube. B3 are complex multipolar regions where spots of opposite polarities are arranged chaotically. We believe that this is the result of the surfacing of several separate flows entangled by turbulence. According to the data of Abramenko et al. [2023], we can conclude that for cycles 23-24, 49% of all AOs were class A groups, 19% were unipolar spots, 19% were irregular bipoles (B1), and 13% were multipolar groups (B2 + B3). However, during periods of cycle maxima, multipolar groups contribute about 40% to the total magnetic flux. But most importantly, these groups are responsible for the production of extreme flares. According to the studies [Abramenko, 2021] of 79 groups with flares stronger than X1.0 in cycles 23-24, 50 groups belong to the B2 and B3 classes. At the same time, the extreme flashes occur in multipoles of class B3.

This kind of information prompts us to change the treatment of irregular groups as a "minor exception" and to deal closely with their properties.

In this paper, we attempted to find common morphological features of powerful and complex AOs of class B3 in the hope that our findings will help to further elucidate the mechanisms of their formation.

2. GENERAL PROPERTIES OF SOME ACTIVE REGIONS OF THE MOST COMPLEX CLASS B3

At first glance, it seems that each complex multipolar active region is unique, and there can be no similarity in the morphological structure of such regions. Another thing is regular bipolar regions, where there is a leading and a tail region, with the leading part usually dominant, the orientation of the group axis follows Joy's law. Even if some empirical rule is not fulfilled, the general configuration of the bipole suggests that we are dealing with a single magnetic tube surfaced from under the photosphere. In the multipolar regions of classes B2 and B3, the spots of different polarity are mixed, but we were able to notice one characteristic feature in their location and, most importantly, in the evolution of the group.

The analysis of the active region of NOAA 12673 (Figure 1) during September 1-6, 2017, when the AO was at longitudes from E25 to W40 (latitude S08), can be considered the starting point of our investigations. At the beginning of the observations, it was a medium-sized unipolar spot twisted clockwise (in full accordance with the rule of vortex twist in the northern and southern hemispheres [Pevtsov et al., 2014]). This spot appears to exist for the third rotation: first as a group leader NOAA 12665 (July 10, 2017) and then as a large unipolar spot NOAA 12670 (August 6, 2017). Around noon September 02, a system of small bipoles begins to pop up south of the spot at a distance on the order of the diameter of the spot itself, forming a looping arcade along an east-west direction. The arcade grows rapidly and wraps around the spot from the east, covering about half of the circumference around the spot by September 3, 11 UT. Further, the pop-up structure almost completely encompasses the spot, but the spot itself remains almost unchanged, with only a slight nudging of its penumbra from the east. It seems that the surfacing structure has a component of the surfacing velocity in the east-west direction and encounters the sub-photospheric vertical backbone of the spot, which strongly deforms it and, possibly, additionally creates favorable conditions for its ascent. Obviously, we are dealing with at least two independent magnetic flows with different dynamics. The strongest flare in this X-ray X9.3 AO turned out to be the strongest in cycle 24.

Other similar examples are shown in Figures 2-5. Thus, Figure 2 demonstrates a situation where a large bipole begins to pop up violently just near the shadow of a large proper leading spot. The orientation of the bipole changes rapidly, so that its leader rounds the main spot from the south and goes to the west. Here, too, we can assume that the pop-up tube encountered an obstacle (the hull of the main leading spot) under the photosphere, which accelerated its pop-up and led to the creation of the δ-structure. This AO produced the strongest flare of cycle 25 so far, X6.4.

Figure 3 shows an example where two bipoles popped up in series in the neighborhood of a spot, and a δ structure was also obtained. In this case, as in the previous examples, the initial spot changes little in both shape and flux, giving the impression that its magnetic structure remains largely independent of what happens in its eastern neighborhood. The strongest flare in the group corresponds to the M9.5 class.

Figure 4 shows the stages of development of NOAA 13664, which turned out to be by far the most powerful by various parameters of flare activity: the most productive in terms of coronal mass ejections, extreme magnetic storms; it also produced GLE74 [Ishkov, private communication]. The strongest flare in it is X5.8. Here, too, the leading western spot stands isolated from the rapidly developing tail zone, even moving slightly to the west of it. The spot grows slowly, collecting the flow of the surrounding pores, and by the end of the observations becomes a regular medium-sized spot with a regular penumbra. The filigree of the supergranulation mesh around it is characteristic of unipolar spots. Images in the SDO/AIA 171A line suggest that most of its flux goes into open or highly closed loops not associated with the AO tail.

Figure 5 shows a rare example of the formation of a class B3 active region, where a violent pop-up of disorderly oriented bipoles is observed to the west of the original unipolar spot. This spot has a magnetic field of positive polarity (white on the magnetograms), which is uncharacteristic of unipolar and leading spots in the southern hemisphere in solar cycle 25. It is unlikely to be considered part of a bipolar structure in conjunction with the western pores, since the AIA images do not show such loop connections. Most likely, this is the main spot of NOAA AO 13685 on the second rotation of its existence, which suggests that here we are dealing with a long-lived magnetic structure rooted rather deep in the convective zone. The strongest flare in the M3.2 group.

The chain of such examples from the data of the current cycle can easily be continued. It is also interesting to look at data from earlier cycles from the same point of view. For example, in Abramenko & Yurchyshyn [2010], Fig. 5 shows magnetograms of four complex active regions of class B3 observed during the decline of cycle 23 (NOAA 10484, 10696, 10720, 10826). The active regions were chosen for other considerations, but for all of them the presence and separate development of a quasi-unipolar spot in the western part of the AO and a complex independent structure in the tail part can be traced. Well-studied from Hinode data, active region 23 of cycle NOAA 10930 (December 7-16, 2006) is also a large unipolar spot, in which a rapidly rotating structure of opposite polarity surfaced near the penumbra. The group produced two powerful flares X3.4 and X1.5. In July 2000 (July 15-26), NOAA 9087 was recorded with SOHO/MDI, a group very similar (down to the anomalous polarity of the original spot) to what is shown in Fig. 5. In the same cycle 23 active region NOAA 9393 (March 23-April 3, 2001), which produced the most powerful flare of cycle 23 X20, the development history also began with the appearance of structures in the vicinity of the large regular spot. The initial phase of development is hidden behind the limb, but during the passage of the group across the disk, a rapid outburst of a close chain of bipolar structures to the south and southwest of the spot, accompanied by increasing flare activity, is clearly traced.

We managed to find an image (Figure 6) of the group of spots of the most powerful for the last two centuries 19th cycle, published in the collection "Development of Astronomy in the USSR 1917-1967" on page 162. It turned out to be the group numbered 19498 by Greenwich Photoheliographic Results (GPR). Unfortunately, no other data about the image are given in the collection, but the article by Gopasiuk et al. [1963] provides data on the magnetic field, confirming our assumption that here, too, there is a configuration of spots similar to that seen in Figs. 3 and 4: an isolated large spot and a close group of multipolar spots. At the same time, the largest spots have the same polarity. The structure as a whole does not confirm the surfacing scenario and the development of an ideal bipolar magnetic tube. The group yielded a proton flare.

3. CONCLUSION

The review of the most complex and interesting magnetic configurations of active regions presented in this paper is by no means intended to be an exhaustive statistical analysis and should be regarded as a pilot project aimed at drawing the attention of the community (primarily scientists involved in dynamo theory, modeling of subphotospheric magnetic flux popping) to the issue of significant systematic deviations from the traditional paradigm about bipolar magnetic tube popping.

Observations suggest the following. Large spots (including unipolar spots), as stable formations, appear to have deep roots and serve as channels facilitating the escape of magnetic structures to the surface. Apparently, convective flows beneath the photosphere on a regular basis create a configuration different in principle from the classical bipolar configuration: a vertical tourniquet-spot and a system of chaotically entangled loops in the vicinity. It was in such magnetic structures that the most powerful flares of the 23rd, 24th, and 25th cycles occurred.

It should be noted that such magnetic structures - a tourniquet-stain plus a tangle of loops - according to the Crimean Magneto-Morphological Classification (CMC) belong to the class of the highest complexity, B3. In general, according to the data for cycles 23 and 24 [Abramenko, 2021], of all 79 groups that produced flares of class X1.0 and higher, 25 belong to class B3. They are also responsible for the extreme flare activity (see Figs. 6,7 in Abramenko, 2021]. Apparently, everything that does not fit within the classical empirical laws [van Driel-Gesztelyi and Green, 2016] is itself ordered and carries the maximum load on the magnetic and flare activity of the Sun.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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FIGURE CAPTIONS

Fig. 1. Developmental stages of NOAA AO 12673 from SDO/HMI instrument observations. Top row - continuum images. The initial unipolar spot is clearly traced on all images. Bottom row - hmi.sharp_cea_720s magnetograms, scaled from -800 Mx $cm^{(-2)}$ (black) to 800 Mx $cm^{(-2)}$ (white). West on the right, north on the top.

Fig. 2. Process of bipole surfacing in the vicinity of a large leading spot with the formation of a δ structure. The designations are the same as in Fig. 1.

Fig. 3. Example of sequential surfacing of two bipoles in the vicinity of a large regular spot. The designations are the same as in Fig. 1.

Fig. 4. Example of a situation in which the leading spot is formed separately and pushed to the west, with independent surfacing of multiple spots of mixed polarity at the tail end. The designations are the same as in Fig. 1.

Fig. 5. Example of surfacing of mixed polarity spots to the west of the main unipolar spot. The designations are the same as in Fig. 1.

Fig. 6. Photogeliogram of a group of spots of the 19th cycle (collection "Development of Astronomy in the USSR 1917-1967. Moscow: "Nauka", 1967, p. 162).

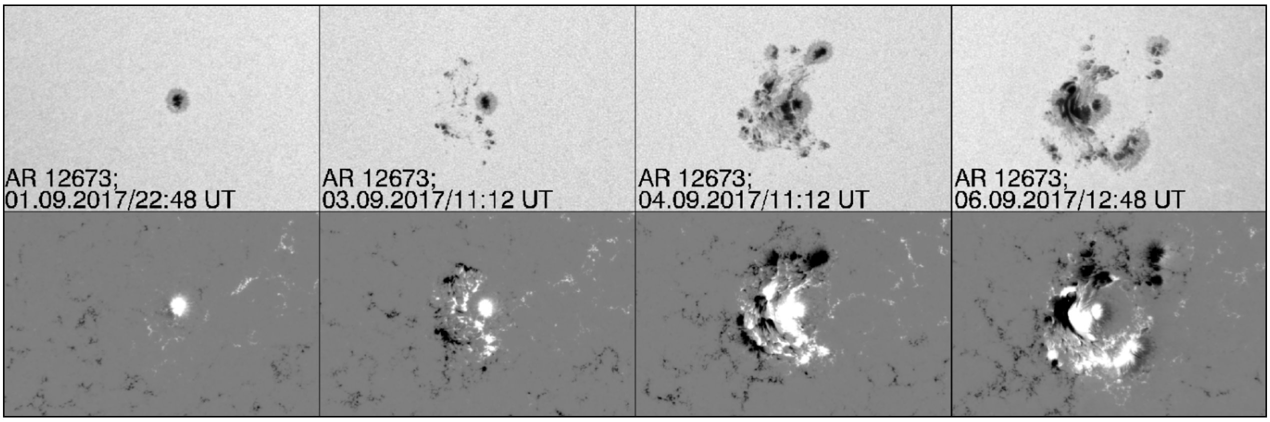

Fig. 1.

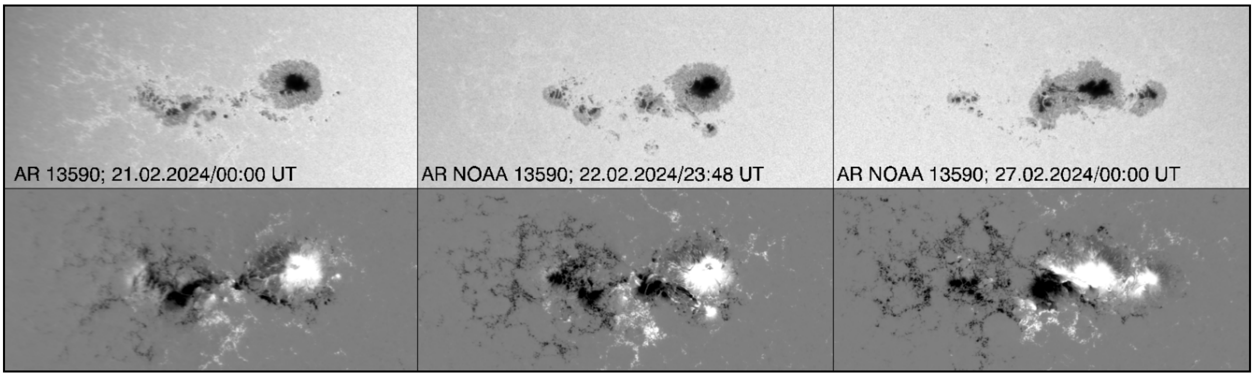

Fig. 2.

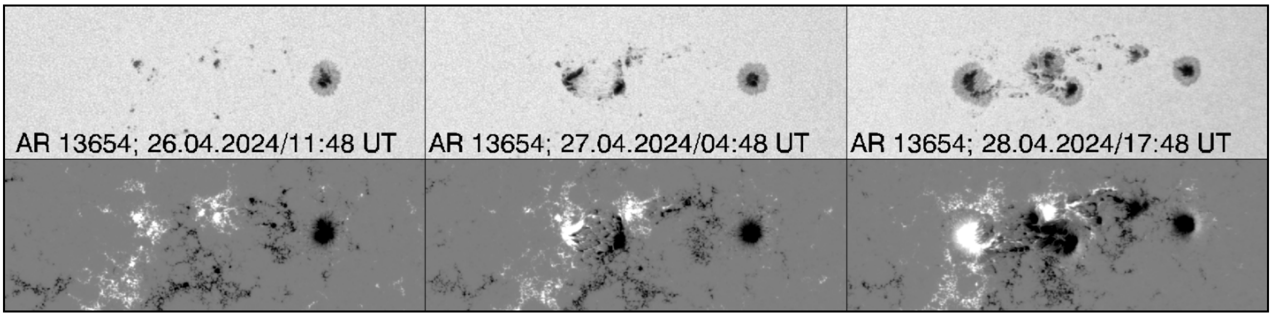

Fig. 3.

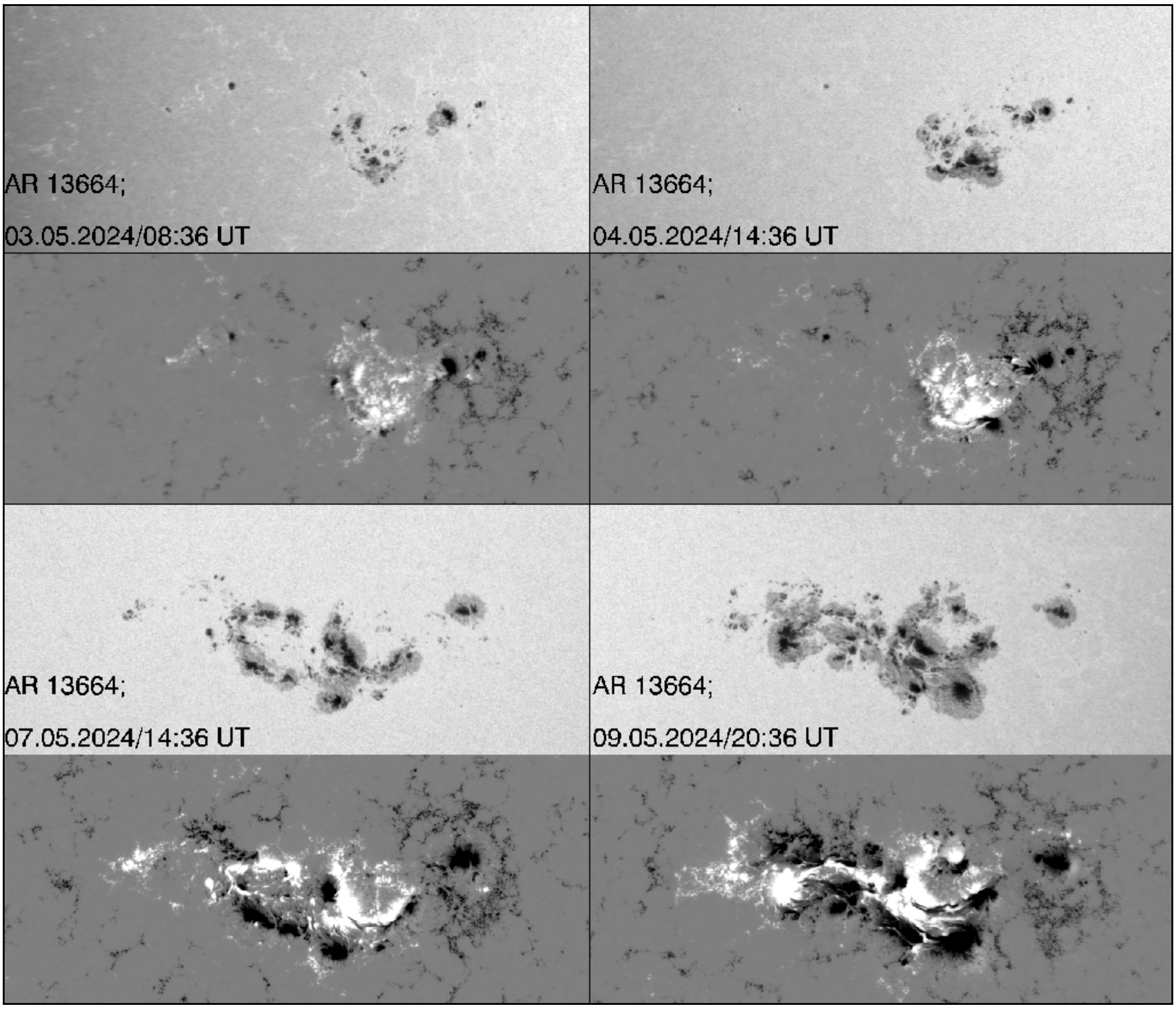
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Fig. 4.

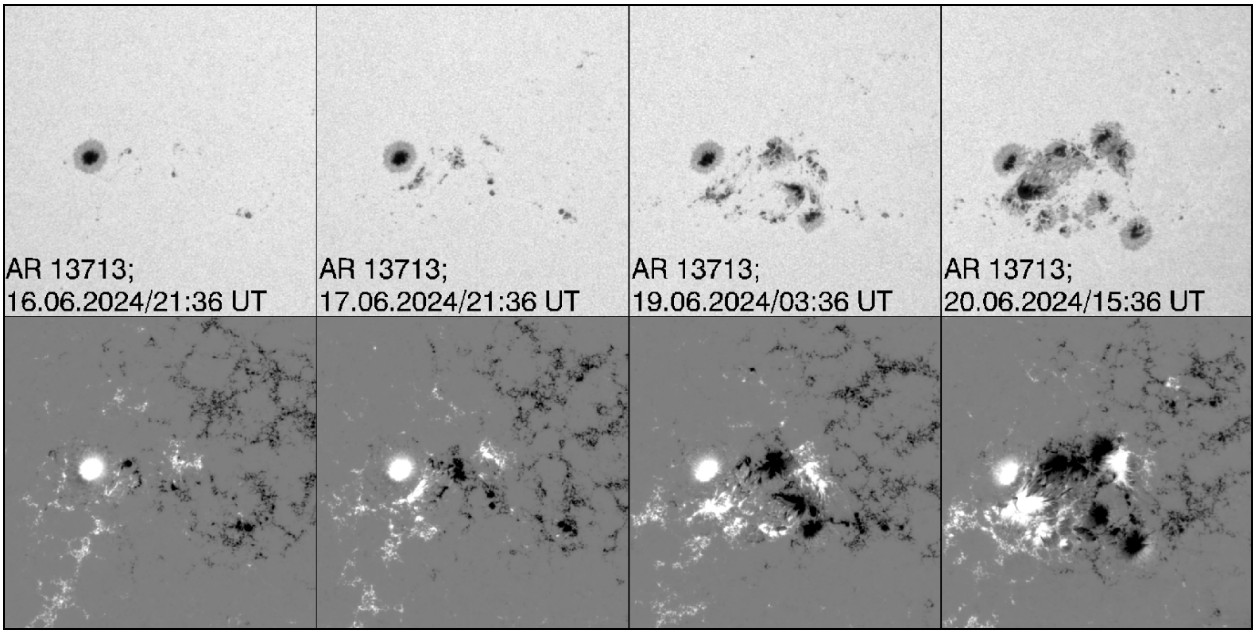
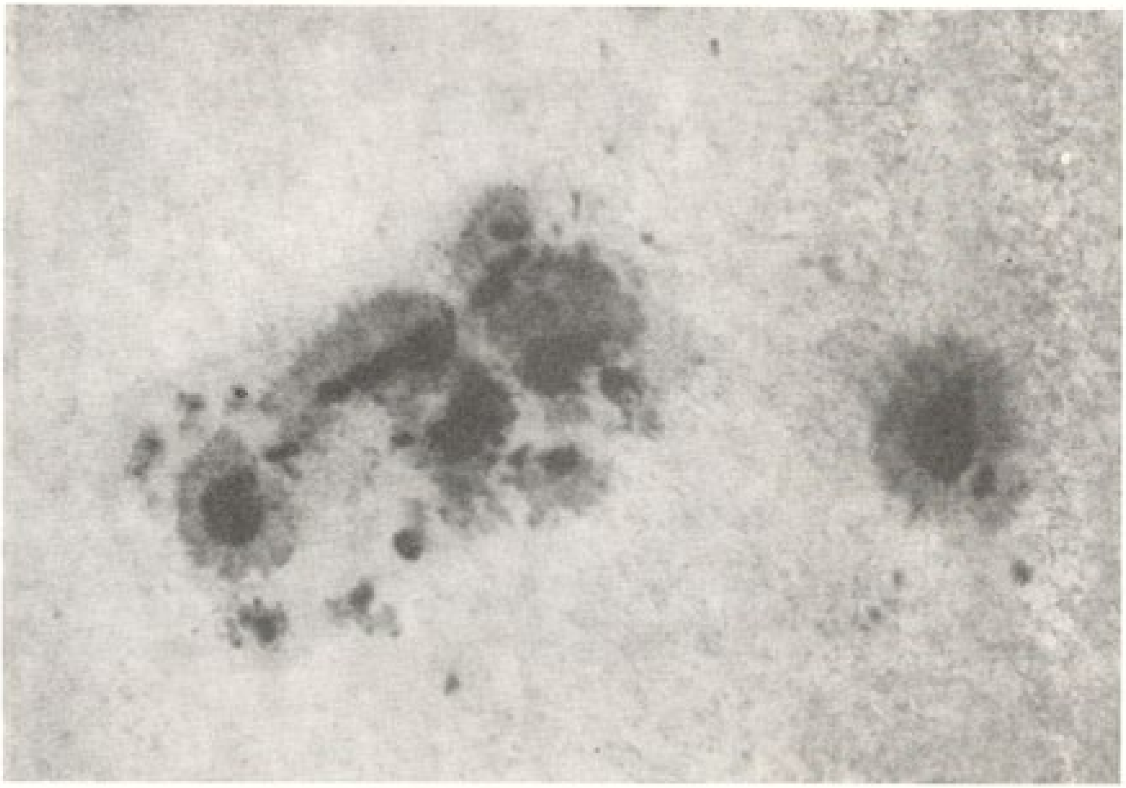


Fig. 5.



Фотография группы солнечных пятен 18 августа 1959 г.

Fig. 6.