https://doi.org/10.18524/1810-4215.2023.36.290216

ANOMALOUS MAGNETIC REGIONS ON THE SUN

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ABSTRACT. We studied the anomalous magnetic regions observed near the minima of solar cycles 24 and 25. The peculiarity of these areas was the deviation of their configuration from Hale's law of magnetic polarity and Joy's law about the inclination of the axes of bipolar groups to the latitudinal direction. Therefore, they belong to the class of so-called anti-Hale active regions. We paid special attention to the flare activity of anti-Hale regions, as this is important for forecasting space weather and magnetic storms in the Earth's atmosphere.

The detected anomalies of the surface magnetism of the active regions studied by us may indicate the influence of the mechanisms of the deep small-scale dynamo on their evolution. In this regard we analyzed the possible mechanisms of the formation of anti-Hale magnetic regions. In particular, such mechanisms can be the mechanisms of a small-scale magnetic dynamo. In connection with this an urgent problem today is the search for observed evidence of the existence of the theoretically proposed by Brandenburg A. et al. (2012) of a new physical entity – a small-scale magnetic field hidden in the solar depths, excited by two qualitatively different mechanisms of a small-scale dynamo (SSD). The first mechanism is the SSD of macroscopic MHD (SSD1), while the second is the diffusion SSD of classical MHD (SSD2). However, the small contributions of these sources are very difficult to distinguish observationally. To solve this complication, Sokoloff, Khlystova and Abramenko (2015) proposed a test for separating the contributions of two sources based on a statistical probabilistic model. Such an important feature of the differences between of the two SSD is the behavior of the percentage of anti-Hail groups of sunspots (in relation to the total number of spots) in the minima of solar cycles. According to statistical studies of long series of observations Sokoloff, Khlystova and Abramenko (2015) found that the percentage of anti-Haile groups of spots increases during minima of the solar cycles, suggesting in favor of SSD2.

We believe that the detected magnetic anomalies of the studied regions may be caused by the influence of a SSD2 in the depths of the convective zone of the Sun, since this source gives the most noticeable contribution to the surface magnetism near cycle minima.

Keywords: solar convective zone, magnetic fields, turbulent dynamo, magnetic activity of the Sun, sunspots, solar flares.

АНОТАЦІЯ. Ми дослідили аномальні магнітні області, що спостерігалися поблизу мінімумів сонячних циклів 24 і 25. Особливість цих областей полягала у відхиленні їх конфігурації від закону магнітної полярності Хейла і закону Джоя про нахил осей біполярних груп до широтного напрямку. Тому вони належать до класу т. зв. антихейлівських активних областей. Ми звернули особливу увагу на спалахову активність антихейлівських областей, оскільки це важливо для прогнозування космічної погоди та магнітних бур в атмосфері Землі.

Виявлені аномалії поверхневого магнетизму досліджених нами активних областей можуть свідчити про вплив на їхню еволюцію механізмів глибинного маломасштабного динамо. В зв'язку цим ми проаналізували можливі механізми утворення антихейлівських магнітних областей. Зокрема, такими механізмами можуть бути механізми маломасштабного магнітного динамо. В зв'язку з цим актуальною проблемою сьогодення є пошук спостережених доказів існування теоретично запропонованої в роботі Brandenburg A. et al. (2012) нової фізичної сутності – прихованого в сонячних глибинах маломасштабного магнітного поля, що збуджується двома якісно різними механізми маломасштабного динамо (ММД). Перший механізм – це ММД макроскопічної МГД (ММД1), а другий – дифузійне ММД класичної МГД (ММД2). Однак мізерні внески цих джерел дуже важко розрізнити за допомогою спостережень. Щоб вирішити цю проблему Sokoloff, Khlystova and Abramenko (2015) запропонували тест для розділення внесків двох джерел на основі статистичної імовірнісної моделі. Такою важливою особливістю відмінностей між двома ММД є поведінка відсоток антигхейлівських груп сонячних плям (по відношенню до загальної кількості плям) у мінімумах сонячних циклів. Відповідно до статистичних досліджень тривалої серії спостережень Sokoloff, Khlystova and Abramenko (2015) виявили, що відсоток антихейлівських груп плям зростає під час мінімумів сонячних циклів, що свідчить на користь ММД2.

Ми вважаємо, що виявлені магнітні аномалії досліджених областей можуть бути викликані впливом ММД2 в глибинах конвективної зони Сонця, оскільки це джерело дає найбільш помітний внесок у поверхневий магнетизм поблизу мінімумів циклів.

Ключові слова: сонячна конвективна зона, магнітні поля, турбулентне динамо, магнітна активність Сонця, сонячні плями, сонячні спалахи.

1. Evolution and flare activity of the anti-Hale active regions

We selected to analysis several anomalous magnetic regions observed near minimum of 24 and 25 cycles of the solar activity. Anti-Hale sunspots regions NOAA 10792, 10715, 10875, 10930, 12673, 13088 are the clear examples of violation of Hale's and Joy's laws. We used the magnetograms obtained by the Helioseismic and Magnetic Imager (SDO) (Scherrer et al., 2012) and the Michelson Doppler Imager (SOHO) (Sherrer et al., 1995).

Active region (*AR*) *NOAA 10792*, first seen on 30 July 2005, in latitude N12, was typical anomalous magnetic region. The magnetic field of this region was not regular. The magnetic poles were rotated 180 degrees compared other ARs in northern hemisphere (Fig. 1). Therefore, this region belongs to the class of anti-Hale magnetic configurations. The oppositely oriented regions occur side by side in the same latitude zone. Therefore, they cannot be part of the same magnetic flux system. The region evolved rapidly, and its most complex magnetic configuration was βγδ. 13 flares of C class and five M class flares occurred in it. One X1.3 class flare was the most powerful. This flare produced a coronal mass ejection (CME).

AR NOAA 10715 (29.12.2004 – 10.01.2005). Active region appeared in latitude N04. The orientation of this anomalous magnetic region differs by 90 degrees from the orientation prescribed by Hale's law (Fig. 2). This fact indicates that fluctuations exist over whole range of orientation angles. The region produced four M class flares, 19 C class flares. The most powerful event was X1.7 class flare.

AR NOAA 10875 (23.04.2006 – 6.05.2006). The region was large and had a complex magnetic field (Fig. 3). Two M class and 15 C class flares occurred in this region. One M8 class flare caused a shortwave radio blackout.

AR NOAA 10930 (5.12.2006 – 18.12.2006*)*. This magnetic region (Fig. 4) produced very high flare activity. There were 31 C class, four M class and three X class flares in this region. One X9.0 class flare was the most powerful. This flare caused a geomagnetic storm.

AR NOAA 12673 (29.08.2017 – 10.09.2017). The region appeared on the solar disk on 29 August 2017 in latitude S08 as unipolar spot and developed rapidly. Orientation of the magnetic region was different by 90 degrees from the orientation prescribed by Hale's law (Fig. 5). The number of the sunspot increased. Its magnetic configuration became more complicated from α up to βγδ. There were 39 C class, 17 M class, and four 4 X class flares in this region. The number of more powerful flares increased over time. One X9.3 class flare was the most powerful. X-ray and UV radiation from this flare caused a strong shortwave radio blackout over Europe, Africa and the Atlantic Ocean. This magnetic region also produced several CMEs and strong geomagnetic storms.

AR NOAA 13088 (24.08.2022 – 30*.08.2022*). The region appeared on 24 August 2022 in the western part of the solar hemisphere and developed rapidly (Fig. 6). The number and the area of the spots increased. The configuration of its magnetic field has become more complex up to βγ class. This region produced 120 C class and 25 M class flares, several CMEs during two transitions through the solar disk. One M8.6 class flare was the most powerful, and one M 4 class flare caused a shock wave through the atmosphere of the Sun and a CME. The magnetic region produced several CMEs and geomagnetic storms.

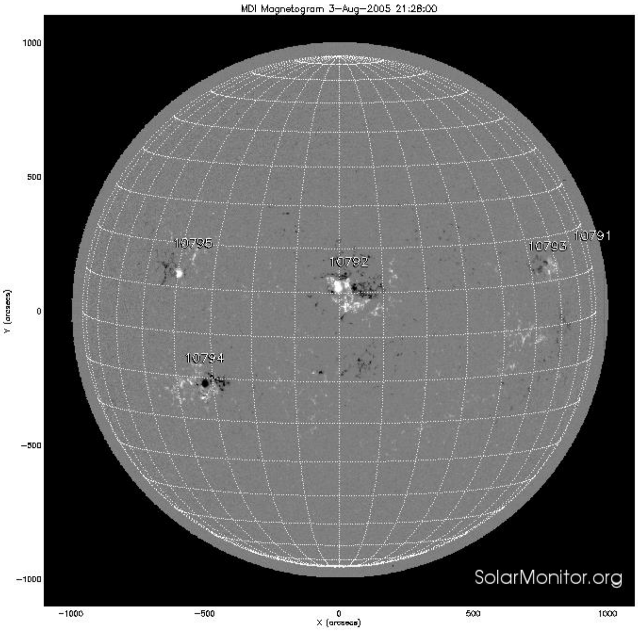

Figure 1: Magnetogram of the Sun on 3 August 2005 (SOHO/MDI). In the center of the figure/disk is the anti-Hale magnetic region NOAA 10792. White and black colors indicate areas of positive and negative polarity of the magnetic field, respectively.

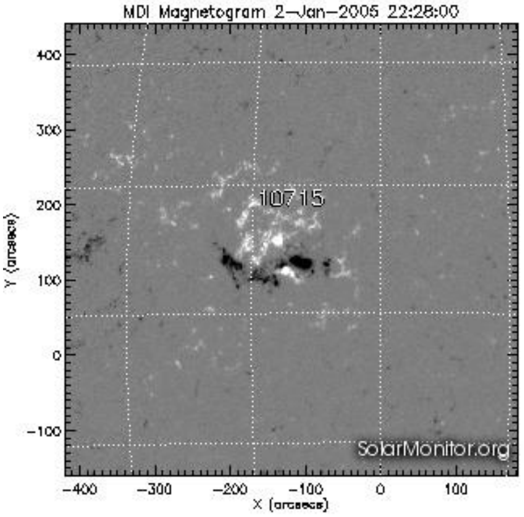

Figure 2: Magnetogram of the active region NOAA 10715 on 2 January 2005 (SOHO/MDI).

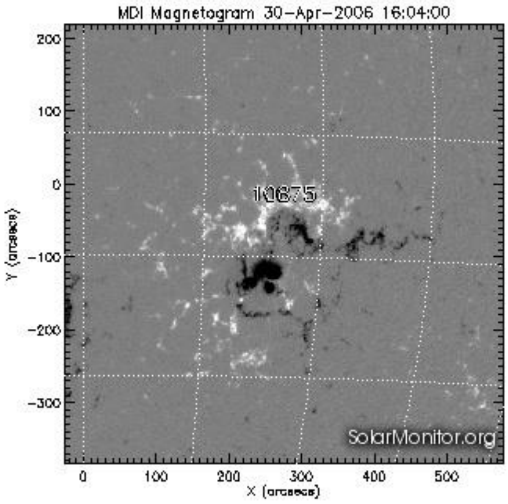

Figure 3: Magnetogram of the active region NOAA 10875 on 30 April 2006 (SOHO/MDI).

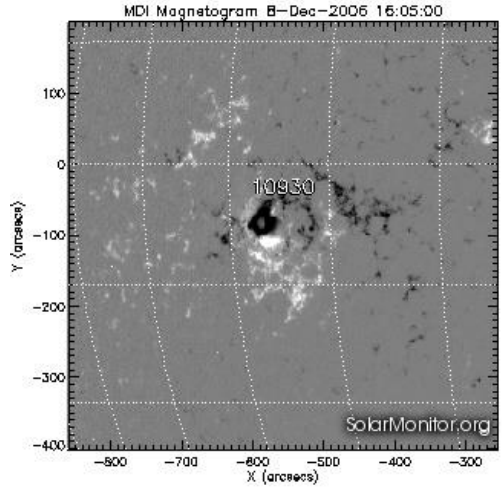

Figure 4: Magnetogram of the active region NOAA 10930 on 8 December 2006 SOHO/MDI).

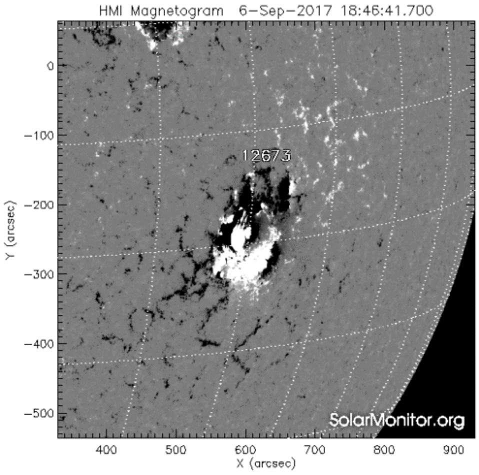

Figure 5: Magnetogram of the active region NOAA 12673 on 6 September 2017 (SDO/HMI).

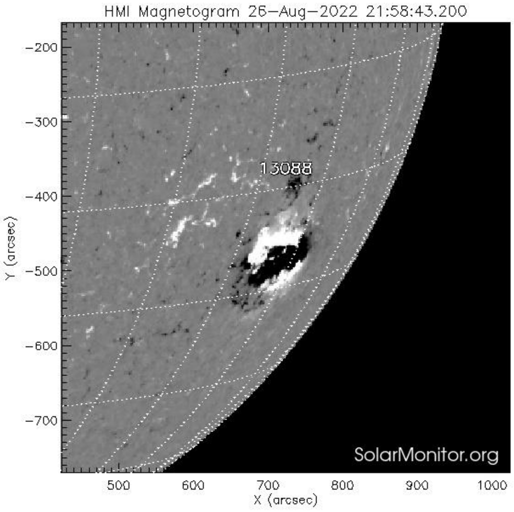

Figure 6: Magnetogram of the active region NOAA 13088 on 26 August 2022 (SDO/HMI).

2. Dynamo mechanisms of small-scale magnetic fields

Next, we will briefly discuss the possible mechanisms contributing to the appearance of anti-Hale active regions [Krivodubskij and Kondrashova, 2023]. In work Sokoloff, Khlystova and Abramenko (2015) based on the processing of observational data for 1920 - 2004 from the Mount Wilson Catalog, it was found that in the “royal zone” a small number of bipolar groups of sunspots were always observed, which had the “wrong magnetic polarity”. Sokoloff, Khlystova and Abramenko (2015) called them “violators of Hale's law”. They believe that the appearance of anti-Hale bipolar groups is related to operation of the small-scale turbulent dynamo in the solar convective zone (SCZ).

Therefore, an urgent problem today is the search for observed evidence of the existence of the theoretically proposed by Brandenburg, Sokoloff and Subramanian (2012) of a new physical entity – a small-scale (fluctuating) magnetic field, excited by mechanism of a small-scale dynamo (SSD), the action of which is hidden in the depths of the SCZ.

Besides, the situation is complicated by the fact that in the depths of the SCZ can function simultaneously two qualitatively different excitation mechanisms of fluctuating fields (small-scale dynamo of macroscopic MHD and the fluctuation dynamo of classical MHD).

The first mechanism ensures the generation of small-scale magnetic fields due to the interaction of turbulent motions with the global magnetic field (small-scale dynamo 1 of macroscopic MHD: SSD1). Within the framework of macroscopic MHD, in the presence of a weak primary magnetic field, two components of magnetism are excited in the SCZ. They are namely next: the global magnetic field **B** and the fluctuating (small-scale) magnetic field **b** (Krause and Rädler, 1980**)**. The excitation of the fluctuating magnetic field **b** (SSD1) is described by the hydromagnetic equation

$$\frac{\partial \mathbf{b}}{\partial t} = \mathrm{rot}\left[(\langle\mathbf{U}\rangle\times\mathbf{b}) + (\mathbf{u}\times\langle\mathbf{B}\rangle) + \mathbf{G} - \nu_m\,\mathrm{rot}\,\mathbf{b}\right],$$

where **U** is the velocity of regular differential rotation, **u** is the velocity of turbulent convection, **G** = **u** x **b** – ⟨**u** x **b**⟩, $\nu_m = c^2/4\pi\sigma$ is the coefficient of magnetic viscosity, σ is the gas-kinetic electrical conductivity.

While the second mechanism (diffusive small-scale dynamo 2 of classical MHD) causes the self-excitation of magnetic fluctuations due to turbulent pulsations of highly conductive plasma (SSD2). Chaotic hydrodynamic movements with velocity **u** excite fluctuating electric currents **j** = - e*n***u** in highly conductive plasma (e is the electron charge; *n* is the concentration of electrons in the plasma). If the magnetic field is frozen in the highly conductive plasma, these fluctuating electric currents **j**, in turn, generate fluctuations of the magnetic induction rot **h** = **j** /(*c*/4π). The amplitude of the generated magnetic fluctuations *h* can be estimated from the condition of equal distribution of the densities of the kinetic $\rho u^2/2$ and magnetic $h^2/8\pi$ energies of small-scale pulsations (Priest, 1982)

$$\rho u^2/2 \approx h^2/8\pi$$

(here ρ is the plasma density).

The fundamental difference between the two quoted small-scale dynamo mechanisms is as follows.

In the SSD1 mechanism, electric currents, which are necessary for the excitation and subsequent reconstruction of magnetism, are generated as a result of the interaction of fluctuating and regular plasma movements ***with the primary magnetic field.***

In contrast, the SSD2 mechanism provides self-excitation of the magnetic fluctuations ***in the absence of a primary magnetic field***. Generation of electric currents is provided by turbulent movements in highly conductive plasma

The small contributions of two sources of small-scale magnetic fields **b** and **h**, localized in the depths of the Sun, to the surface magnetism are very difficult to distinguish with the help of observations.

Therefore, researchers face the fundamental physical problem of how to find tiny surface manifestations of the small-scale action of two dynamo mechanisms in the interior of the Sun.

3. Search for surface tracers of a deep small-scale magnetic dynamo

Sokoloff, Khlystova and Abramenko (2015) assumed that tracers of small-scale dynamo action in the interior of the Sun may be hidden in the statistics of bipolar groups of sunspots, which violate Hale's law of magnetic polarity and Joy's law of inclination of the axes of bipolar groups to the latitudinal direction. The essence of the proposed criterion is that deep small-scale magnetic fields under certain conditions can lead to violations of Hale's and Joy's laws of observed magnetism on the surface of the Sun.

According to Hale's law of east-west magnetic polarity orientation (Hale et al., 1919; Hale and Nicholson, 1925) during one 11-year cycle in one hemisphere (northern or southern), the head and tail spots of bipolar magnetic groups always have the same opposite magnetic signs. On the other side of the equator, the signs of the head and tail spots are opposite. This situation persists throughout the current cycle, and then, when a new cycle begins, the signs of the spots are reversed. At the same time, the axes of bipolar groups of spots are oriented at a small angle to the "east-west" latitudinal direction (Hale et al., 1919), so that the western head (leading in relation to rotation) spots are on average closer to the equator than the eastern tail spots (Joy's law of magnetic polarity orientation north-south). The average tilt angle of the axes of bipolar groups is about 4°, increasing from a few degrees (for groups near the equator) to 8-10° for high-latitude groups (Howard, 1991).

Hale and Nicholson (1925) as a result of statistical analysis of bipolar groups of spots from 1913 to 1924, found that 2.4% of active regions do not obey the law of magnetic polarities of groups established by them. Similar estimates of the deviation from Hale's law were obtained in subsequent studies by many authors over almost a century. As for the violations of Joy's law, they are to a greater extent characteristic of the anti-Hale bipolar groups of spots. More 70 years ago Richardson (1948) found that in anti-Hale groups, the tilt angles of their axes relative to the equator are, as a rule, greater than the tilt angles of groups of spots that comply with Hale's law.

The study of tilt angles of active magnetic regions allows us to make assumptions about the mechanism of the emergence of anti-Hail groups of spots and its localization in the SCZ. In paper (Munoz-Jaramillo, Navarrete and Campusano, 2021), the inclinations relative to the equator of regular and anti-Hale groups covering four solar cycles were studied. Anti-Hail groups were found to belong to a separate population. This indicates the mechanism of their origin, which differs from the excitation of a regular toroidal field by the Ω effect. In particular, Bekki and Cameron (2023) found that violations of Joy's law are inherent to bipolar magnetic regions shallowly rooted in the subphotospheric convection layers. Therefore, it can be assumed that this mechanism is a subsurface fluctuating small-scale dynamo.

Statistical analysis of deviations from Hale's and Joy's laws over long periods of time allows us to reveal differences in the evolution of the observed manifestations of the two sources of small-scale fields **b** and **h**, since the contribution of the two deep dynamo mechanisms to the surface magnetism changes with the phase of the solar cycle in different ways.

Such an important feature is the behavior of the of anti-Hail groups of sunspots during the cycles. In the case of small-scale dynamo 1 (magnetic field **b**), the percentage of anti-Hale groups is independent of cycle phase. Whereas the percentage of anti-Hale groups associated with small-scale dynamo 2 (magnetic field **h**), should reach its maximum value at solar minima, as the global toroidal magnetic field weakens at this time.

Therefore, the variations of magnetic anomalies make it possible to separate the tiny contributions of deep two small-scale dynamo mechanisms to surface magnetism. In this connection, the task of identifying the harbingers of a small-scale dynamo in the solar depths from observations is gaining relevance.

With this in mind, we conducted an analysis of literature data of statistical studies of long series of observed violations of Hale's and Joy's laws, which can be caused by the presence of deep small-scale magnetic fluctuations of various origins.

In the work Sokoloff, Khlystova and Abramenko (2015) on the basis of processing the data of different catalogs for the period 1917 - 2004, it was demonstrated that the percentage of anti-Hale groups of spots increases during the minima of solar cycles. This testifies to the operation of a random small-scale turbulent dynamo 2 (diffusive dynamo) within the SCZ, the efficiency of which becomes noticeable near the minima of the cycles, when the global toroidal magnetic field weakens.

In this regard, we note the two-layer dynamo models proposed in papers of Benevolenskaya (1998), and Popova, Zharkova and Zharkov (2013). These models are based on the idea of two dynamo sources separated in space. The first dynamo source is located near the bottom of the SCZ, while the second one operates near the solar surface. Currently, it seems that the near-surface source of excitation in the two-layer dynamo models is consistent with the theoretical concept of the excitation of magnetic fluctuations by the mechanism of the *diffusion* small-scale dynamo 2, which is localized in the upper part of the SCZ.

4. Discussion and conclusions

We selected to analysis several anomalous magnetic regions observed ***near minima*** of 24 and 25 cycles of the solar activity. The peculiarity of these ARs consisted in the deviation of their observed surface magnetic configuration from Hale's law of the magnetic polarity of spot groups and Joy's law of tilting the axes of bipolar groups to the latitudinal direction.

In recent decades, thanks to the use of data from observations of space vehicles, evidence has emerged that rare superactive ARs which violated Hale's and Joy's laws had a strong tendency to produce X-ray bursts, strong proton events, and strong magnetic storms (Tian et al., 2002; Tian et al., 2005; Abramenko, 2021; Xu et al., 2022). With this in mind, we paid attention to the flare activity of anti-Hale regions. It was established that all ARs investigated by us generated significantly high flares activity. Considering the relevance of detecting periods of increased levels of flares for the purpose of space weather forecasting, the study of Ars, characterized by violations of Hale's and Joy's laws, becomes important.

We analyzed two qualitatively different possible dynamo-mechanisms of formation of anti-Hale magnetic regions. In the case of small-scale dynamo 1 (macroscopic MHD), the percentage of anti-Hale groups is independent of cycle phase, whereas the percentage of anti-Hale groups associated with diffusive small-scale dynamo 2 (classical MHD) should reach its maximum value at solar minima.

The ARs studied by us were observed near the minima of cycles 24 and 25. Therefore, we assume that the detected observed magnetic anomalies may indicate the influence of the fluctuating small-scale diffusion dynamo 2 of the classical MHD on the evolution of the studied ARs, since this source gives the most noticeable contribution to the surface magnetism ***near the cycle minima***.

Acknowledgements. The work was carried out with the support of the Ministry of Education and Science of Ukraine, state budget grant number 22BF23-03 under the program "Astronomy and space physics" of Taras Shevchenko National University of Kyiv.

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