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Temporal and Latitudinal Distribution of anti-Hale Active Regions in the Synthetic Solar Cycle

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1. Abstract.

The polarity of leading sunspots in active regions (ARs) is determined by the direction of the toroidal component of the global solar magnetic field. The vast majority of bipolar ARs have the certain leading sunspot polarity in accordance with the Hale's polarity law, whereas some ARs have the opposite polarity (anti-Hale ARs). The number of such groups is relatively small (about 4%), which complicates some important tests. The data on 14838 ARs (including 367 anti-Hale groups) related to five 11-yr cycles (16–18 and 23, 24) were combined in a synthetic cycle of unique time length and latitudinal width. A specific routine was created for this purpose. Our analysis of the synthetic cycle shown that anti-Hale ARs follow the cycle and their time-latitude distribution quite uniform, which implies their genetic connection with the global dynamo. The higher values of anti-Hale ARs percentage near the equator may be explained by the misalignment between the magnetic and heliographic equators. The increase in the number and percentage of anti-Hale ARs that occurs in the second part of the cycle might indicate the relationship with the process of the polar field reversal. The increase in the percentage that found in the solar minimum and at the edges of the butterfly diagram (zones where the magnetic field is weakened) might indicate facilitation of the processes that distort flux tubes during their rising through the convection zone. In addition, the synthetic cycle compilation method might be used for studying other magnetic activity tracers with poor statistics.

Keywords: solar cycle; solar active regions; solar magnetic fields.

2. Introduction

The magnetic cycle models explain the phenomenon of the solar activity, however some aspects are not fully understood. According to modern concepts based on the classical models [*Parker*, 1955; *Babcock*, 1961], the solar magnetic fields generation implies the mutual transformation of the poloidal and toroidal components of the global solar magnetic field occurring inside the convection zone with approximate period of 11-yr. In each given solar cycle (SC), it is the direction of the toroidal field that determines the characteristics of active regions (ARs) that appear on the solar surface. In accordance with the Hale polarity law [*Hale et al.*, 1919], in even cycles, the bipolar ARs have the negative polarity of the leading sunspots in the north and positive in the south hemispheres; the polarity in the odd cycles is opposite. The appearance of ARs violating this rule (anti-Hale ARs) does not fit into the framework of the magnetic cycle models and cannot be explained by the global dynamo action in terms of the mean field dynamo theory [*Krause and Rädler, 1980*]. Note that ARs with violations from other empirical rules for sunspots groups (for example, Joy's law) are not considered here.

However, some essential tests cannot be carried out for anti-Hale ARs, since the relatively small number of such ARs does not provide the sufficient reliability of statistical studies. The relative number of anti-Hale groups is reported of about 4% by the authors, who tested each AR individually (see *Zhukova et. al.,* 2020 and references therein); the same results were shown in some studies on the base of automatic ARs extraction algorithms [*Stenflo and Kosovichev,* 2012]. To overcome the anti-Hale ARs statistical limitations, we propose combining the available data on the anti-Hale groups of five SCs (16–18 and 23, 24). Thus, the purpose of this work is to form a sample sufficient for a meaningful study of the time-latitude distribution of anti-Hale ARs.

3. Data and method

As data source on anti-Hale ARs of SCs 23 and 24, we used the Catalogue of bipolar ARs violating the Hale polarity law from 1989 to 2018 [*Zhukova et al.*, 2020], and its prolongation (2019–2020) at http://sun.crao.ru/databases/catalog-anti-hale. We also used the Summary of Mount Wilson magnetic observations of sun-spots (SMWMO) as the source of the information about reverse-polarity ARs for the period from 1925 to 1958 (SCs 16–18). The Summary was published in the Publications of the Astronomical Society of the Pacific. The SMWMO data are available in digital form at http://iopscience.iop.org/journal/1538-3873. Data on all ARs observed on the disk during these periods were obtained from the USAF/NOAA Solar Region Summary (SRS) at http://solarcyclescience.com.
The first task was to determine a hosting SC for each individual AR (the groups of both the preceding and following cycles appear on the disc simultaneously in the solar minimum). To define the boundaries between the cycles, we used the USAF/NOAA SRS data and the method proposed by *McClintock et al.* [*2014*]. The next task was to combine the cycles, taking into account their different duration and amplitude. Butterfly wings of different cycles don't match well as it is shown in Figure 1 (left panel) for SCs 23, 17. However, the cycles are known to be similar and can be stretched or compressed [*Hathaway*, 2015]. We performed a linear transformation of each of the separated cycles in both time and latitude coordinates so that the wings match (Figure 1, right panel). The moment when ARs of the cycle begin to emerge regularly (at least two or three ARs per month) was accepted as the zero-point T0. The equatorial line was accepted as the natural latitude divider and was marked as L0. The lines T1 and L1 bound the SC 23, whereas the lines T2 and L2 outline the SC 17.

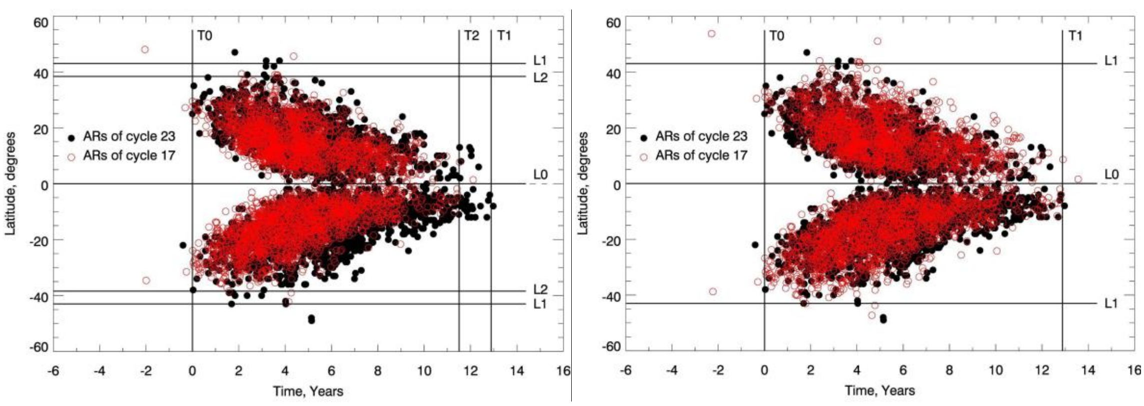

Figure 1. *Overlapping of ARs of SCs 23 (black) and 17(red) before (left panel) and after (right panel) the linear transformation.*

The same routine was also performed for the rest three cycles. More details can be found in *Zhukova et al.* [*2022*].

4. Results

The temporal variations of ARs in the synthetic cycle are presented in Figure 2. The beginning and end of the synthetic cycle correspond to the period of the real SCs overlapping (when low-latitude ARs of the previous cycle and high-latitude ARs of the following cycle appear on the disk simultaneously). Since that the duration of the synthetic cycle is slightly longer than 11 years (about 13 years). One can see that anti-Hale ARs follow the cycle, which implies their mutual connection with the global dynamo and organized toroidal flux system in the convection zone.

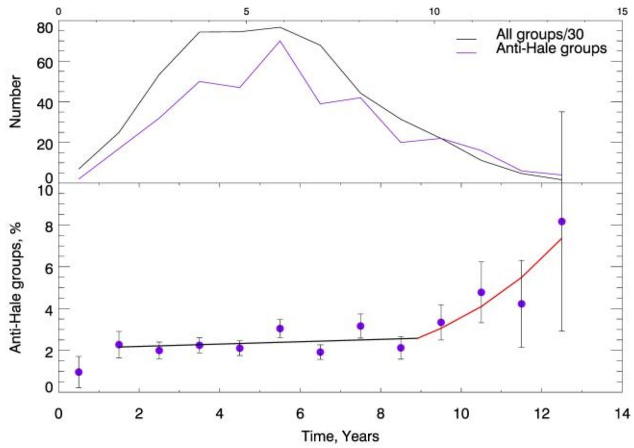

Figure 2. *Temporal variations of all ARs (thin black line) and anti-Hale groups (violet line) in the synthetic cycle (top panel). Yearly values of the relative number of Anti-Hale ARs are shown with violet circles (bottom panel). Thick black and red lines represent the fitting with linear and exponential functions, respectively.*

We also performed the coupling of two identical individual synthetic cycles, placing them one after the other (Figure 3). It allowed us to simulate the adjunction of cycles in the solar minima. We used different overlap intervals (one, two, three years). The intervals of one (Figure 3, left panel) and two (Figure 3, right panel) years are consistent with the real pattern for SCs, as it is following from the typical butterfly diagrams. Using both overlap intervals showed the peaks in the anti-Hale ARs percentage in the simulated minimum, which is consistent with findings by *McClintock et al.* [2014]; *Sokoloff et al.* [2015]. The increase in the anti-Hale ARs percentage in solar minima is interpreted by the authors of these works in different ways. *McClintock et al.* [2014] associated this phenomenon with misalignment between the magnetic and heliographic equators. At the same time, *Sokoloff et al.* [2015] discussed a possible small-scale cycle-independent dynamo action. Their idea was that such a process could be noticed at intervals when the global dynamo action is least pronounced.
The time-latitude distribution of anti-Hale ARs and their relative number in the synthetic cycle are presented in Figure 4 (left and right panels, respectively). It can be noticed that the fraction of anti-Hale groups is increased near the equator. This supports the hypothesis of the misalignment between the magnetic and heliographic equators [*McClintock et al.*, 2014]. Such a misalignment was found earlier by [*Zolotova et al.*, 2009]. However, the increase in the anti-Hale ARs percentage is also observed on different latitudes near the oncoming solar minimum.

It might be the evidence of the more complex shape of the equator, which was reported by [*Obridko et al.,* 2011].

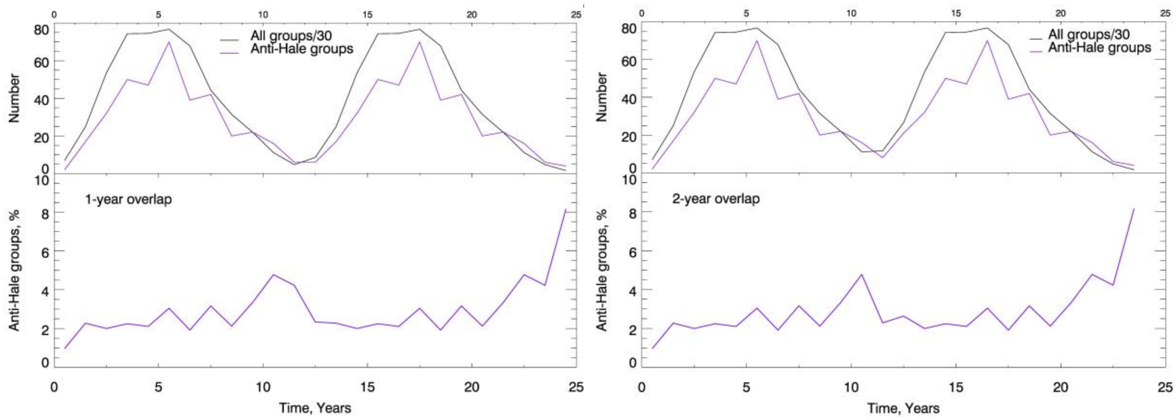

Figure 3. *Temporal variations of ARs in the doubled synthetic cycle with different overlapping intervals: one (left panel) and two (right panel) years.*

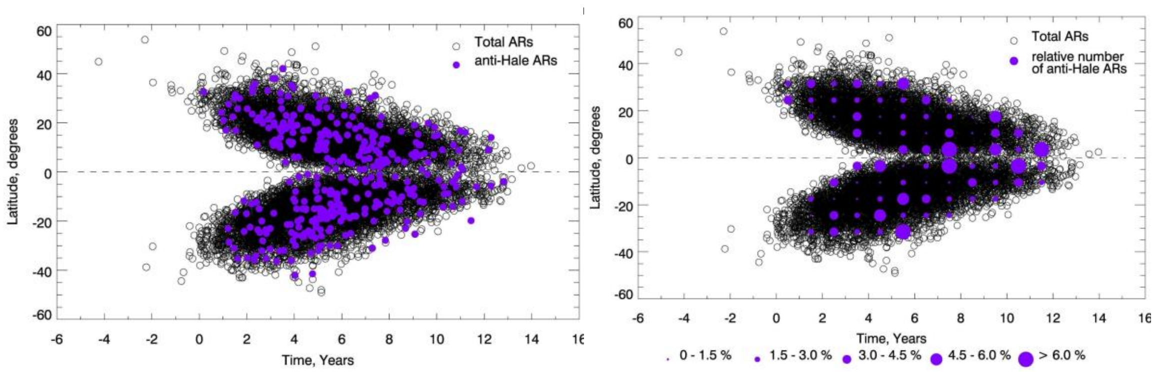

Figure 4. *Time-latitude distribution of ARs in the synthetic cycle: anti-Hale ARs (left panel), the relative number of anti-Hale ARs (right panel).*

We also found the increase in the anti-Hale ARs relative number at the edges of the butterfly diagram. The interval near the oncoming minimum is a zone of the weakening of the toroidal field and the smallest activity of the global dynamo, which was discussed by [*Sokoloff et al.*, 2015*; Abramenko et al.*, 2018]. The edges of the diagram are also implies the weakened field. We can assume that the weakening and loss of regularity of the toroidal field facilitate the manifestation of the mechanism(s) that distort magnetic flux tubes of ARs during their rising through the convection zone. Strong convective flows and magnetic field fluctuations and, hence, the turbulent component of the dynamo can cause the distortion of tubes [*Abramenko,* 2021].

Recall that the beginning and end of the synthetic cycle correspond to the period of the real SCs overlapping and relate to the solar minimum. At the beginning of the cycle, the fraction of anti-Hale ARs is very small, whereas at the end of the cycle the anti-Hale ARs percentage is increased (Figures 2, 4). We speculate that the strong regular toroidal field of the new cycle pushes to the surface the weakened toroidal field of the old cycle at that period, which leads to the increase in the anti-Hale ARs percentage.

In generally, the increase in the number and percentage of anti-Hale ARs occurs in the second part of the cycle, which is consistent with the idea of the relationship of the reverse-polarity ARs and the process of the polar field reversal [*Mordvinov et al.*, 2022].

5. Conclusions

Based on the results obtained we make the following conclusions:

1. The temporal variations of anti-Hale ARs are consistent with the cycle progress, which implies the genetic relationship with the global dynamo and the toroidal flux system in the convection zone.
2. The temporal variations of the relative number of anti-Hale ARs show the peak in the minimum simulated by the coupling of two identical individual synthetic cycles, which might mean the weakening of the produced by the global dynamo toroidal field and intervention mechanism(s) that distort magnetic flux tubes of ARs during their rising through the convection zone (for instance, the turbulent component of the dynamo).
3. The time-latitude distribution of the relative number of anti-Hale ARs shown the increase in the edges of the butterfly diagram and near the oncoming minimum of the synthetic cycle (zones of the weakening of the toroidal field), which might indicate facilitation of the mechanism(s) that distort magnetic flux tubes of ARs.
4. The increase in the anti-Hale ARs relative number near the equator at different latitudes might mean a displacement of the magnetic equator relative to the heliographic equator and, moreover, a complex shape of the magnetic equator.

The synthetic cycle compilation method might be used for studying the time-latitude distribution of other magnetic activity tracers with poor statistics (not only anti-Hale ARs).

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