BIPOLES IN THE EXTENDED SOLAR ACTIVITY CYCLE

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Abstract. The properties of magnetic bipoles have been analyzed. For this purpose, magnetic bipoles of different sizes are identified based on SDO/HMI magnetic field observations in the period 2010-2024. The distribution of bipoles in the solar cycle as a function of magnetic polarity in Hale's law is considered. It is shown that magnetic bipoles of polarity corresponding to the current 22-year magnetic cycle appear at high latitudes 2-4 years before the appearance of the first sunspots. This distribution of magnetic bipoles corresponds to the hypothesis of an extended activity cycle. The dependence of the length of the magnetic axis of bipoles *l on* the area of magnetic bipoles has been studied. It is shown that there is a local maximum of the parameter *l* corresponding to the distances *l~20* and 86 Mm. A bipole distribution diagram in the coordinates til-angle τ of the magnetic axis length *l* is plotted. The *l-τ* diagram shows inhomogeneities possibly related to the influence of supergranulation on the bipoles.

Keywords: *Sun, sunspots, magnetic bipoles, extended activity cycle*

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1. INTRODUCTION

The amplitude of the Sun's magnetic field varies regularly with a periodicity close to 11 years. Each new sunspot cycle begins at mid-latitudes and slowly (over a period of about 9 years) migrates toward the equator, taking the shape of a butterfly's wing. The discovery that sunspots are sites of strong magnetic fields [Hale, 1908; Hale et al., 1919], and that the butterfly wings alternate magnetic polarity in each hemisphere of the Sun, led to the conclusion that the Sun's magnetic field reverses polarity about every 22 years. Sunspots tend to appear as pairs, active regions (ARs). The leading polarity of an AO is closer to the equator, and the angle of inclination between the two polarities relative to the equatorial plane depends on the latitude of occurrence (greater angle of inclination at higher latitudes of occurrence). This pattern is also known as "Joy's law" [Hale et al., 1919)].

The magnetic field on the surface of the Sun manifests itself as a large variety of magnetic structures that vary considerably in both size and total magnetic flux content. The largest of these structures form ARs, bipolar magnetic regions (BMRs) associated with sunspot groups, which are characterized by regions of floccules, pores, and sunspots. At the same time, there are small BMRs that are not associated with sunspots. Small BMRs appear on the Sun's surface even when the Sun is relatively quiet. The smallest of them are called ephemeral regions (ERs) [Harvey & Martin; 1973; Harvey, 1993]. They have short lifetimes, typically a few hours to one day. Ephemeral regions appear at high latitudes several years before the sunspot cycle begins and continue at low latitudes for several more years after the sunspot cycle ends. This pattern of activity is called the extended solar cycle (ESC) [Harvey, 1993; Wilson et al., 1988]. The emergence and evolution of the BMR, as well as the evolution of the global properties of the solar magnetic field, are critical to understanding the solar cycle and dynamo action in general.

The concept of an extended solar cycle has now been developed, including the distribution of bright regions from UV observations, torsional oscillations, and solar coronal intensity [see reviews by Martin, 2024; McIntosh et al., 2021]. At the same time, it is not always possible to obtain ESC manifestations in the distributions of magnetic bipoles [Hofer et al., 2024]. However, it is the magnetic bipoles that can unambiguously confirm the existence of ESC, since other tracers can be associated with secondary manifestations. In this paper, we investigate the properties of the Sun's magnetic bipoles, including small-sized bipoles.

2. DATA AND DATA ANALYSIS

As initial data we used magnetograms obtained at the SDO/HMI space observatory magnetograph during the period 2010.06-2025.02 with an exposure of 45 sec. of the hmi.M_45s series. We took 5 images for each day at time points close to 00:00, 05:00, 10:00, 15:00, and 20:00 UT. The following procedure was used to extract magnetic bipoles. Initially, magnetic elements whose magnetic field intensity exceeded some threshold level were selected. For SDO/HMI magnetograms, this level was $Bt = \pm 50$ Gs. Magnetic elements of less than 20 mdp were not considered. The choice of such thresholds was justified in Tlatov et al (2010). The magnetic field on the full disk magnetograms was considered radial. Next, the procedure of bipolar elements extraction was performed. For this purpose, for each positive region, we found a paired negative region having a close value of the magnetic flux $abs(\Phi- + \Phi+)/ abs(\Phi- - \Phi+)<50\%$ and located at the minimum distance dp. The same procedure was performed for the negative regions, for which the corresponding positive region was found at the minimum distance dn. If the selected pairs matched, it was considered that the bipolar region was identified [Tlatov et al, 2010].

To identify the orientation of the bipoles, we considered the angle formed between the vertical and the ray from the center of the positive element toward the negative element. The direction of the magnetic axis of the bipole to the east was taken as positive, the direction to the west as negative. During processing, we could use different filters, primarily by selecting bipoles in the desired range of area and distance from the central meridian.

3. RESULTS

Figure 1 shows the distribution of magnetic bipoles in the area range S: 20-300 mdp, which corresponds to the area typical of ephemeral regions on the Sun. The color of the area depends on the predominant sign of the magnetic axis direction. Red in the direction from the positive element to the negative element to the east, blue to the west. The total number of isolated bipoles amounted to about 110 thousand.

In Figure 1, we see large-scale structures starting at high latitudes and ending at the equator. This is consistent with the concept of an extended activity cycle. The ESC regularities extend the wings of the activity butterfly back in time, 6-8 years before the appearance of sunspots and at higher solar latitudes. The appearance of magnetic bipoles is closely related to the 11-year activity cycle. The largest number of bipoles is located in the region of sunspots existence. The direction of the magnetic axis of bipoles of ephemeral regions at middle and low latitudes corresponds to the direction of the magnetic axis of AR in the Hale cycle. But we also see preferential bipole directions at high latitudes ~50-60 °.

Figure 2-4 summarizes the properties of magnetic bipoles. The size of the magnetic axis, i.e., the distance between the positive and negative magnetic centers *l* , is not monotonic. Figure 2 shows the distribution of the relative number of bipoles as a function of the distance *l*. In the distribution of the magnetic axis length of the bipoles, local maxima around *l* are visible ~20 Mм and86 Mm. Previously, local maxima in the magnetic axis length distribution of bipoles were found when analyzing sunspot bipoles from 100 years of magnetic field measurements at Mount Wilson Observatory [Tlatov and Tlatova, 2018]. In this work, a maximum in the distribution was found for the length l~85 Mm, which is close to the results of this analysis.

The non-monotonicity of the distribution of distance *l is* confirmed by Figure 3, which shows the variation from the magnetic flux of the bipoles. The local minimum of distance *l* falls at flux values F~2 10^{21}Mx.

We also considered the relationship between the tilt angle and the size of the magnetic axis of the bipoles. Fig. 4 shows the distribution of the relative number of bipoles in the distance-tilt-angle coordinates. In Fig. 3 we see local maxima in the l-τ coordinates. In general, the bipoles have a positive angle of inclination of the magnetic axis τ. This is consistent with the property of Joy's law, so that the tails of the magnetic bipoles of sunspots are closer to the poles than the regions of leading polarity.

3. CONCLUSIONS

In this paper we have considered the characteristics of the magnetic bipoles of sunspot fields from data processing of HMI/SDO telescope magnetic field observations in the period 2010-2024.

We identified localized regions with increased magnetic field intensity and composited the magnetic bipoles. We plotted the distribution of small-size magnetic bipoles in latitude-time coordinates (Fig. 1). In Figure 1, we see large-scale patterns of magnetic bipole distributions starting at high latitudes and ending near the equator. Bipoles with the direction of the magnetic axis corresponding to the direction of the next activity cycle appear at high latitudes 3-5 years before the beginning of the sunspot cycle. This pattern is consistent with the hypothesis of an extended activity cycle [Wilson et al., 1988].

For the magnetic axis length *l,* there are local maxima of *l~20* Mm and86 Mм (Figs. 2,3). The minimum of the parameter *l* occurs at a flux of ~ F~2 10^{21}Mx. This value corresponds to sunspots S~100 mdp or bipoles S_b~2x50 mdp. Earlier works (see e.g. Tlatov, 2023) have shown that there are different properties in the magnetic field intensities and lifetimes of sunspots and pores with areas larger or smaller than this value.

The reasons for the existence of preferential sizes in the *l* distribution can be understood from the tilt-length density diagram of the magnetic axis of *l-τ* bipoles (Fig. 4). In [Tlatov and Tlatova, 2018], a hypothesis about the possible influence of supergranulation on the position of magnetic bipoles was suggested. Figure 4 confirms this hypothesis. Indeed, if we assume that the magnetic elements of small-sized bipoles tend to be located in the gaps between the supergranules, we should observe a wispy distribution in the *l-τ* coordinates. This is exactly the distribution we observe in Figure 4.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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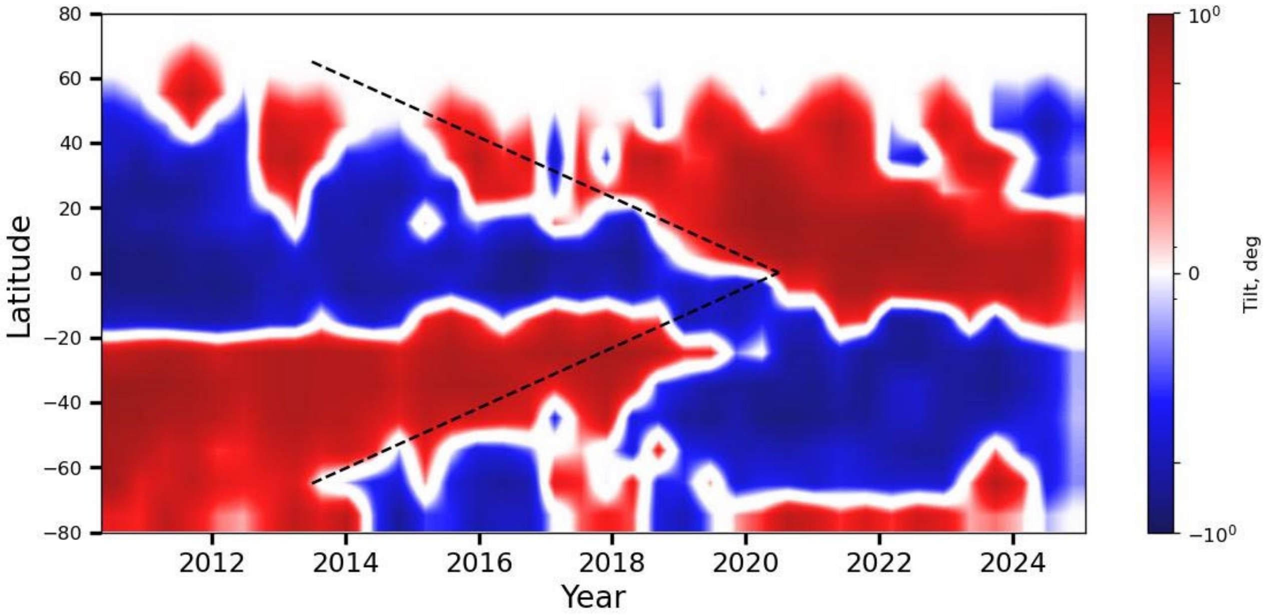
FIGURE CAPTIONS

Fig. 1. Distribution of bipoles of area S:20-300 mdp. The color depends on the sign of the direction of the magnetic axis. Red in the direction from the positive element to the negative element to the east, blue to the west. The dotted lines limit the possible areas of cycle separation.

Fig. 2. Distribution of the relative number of bipoles as a function of the magnetic axis size.

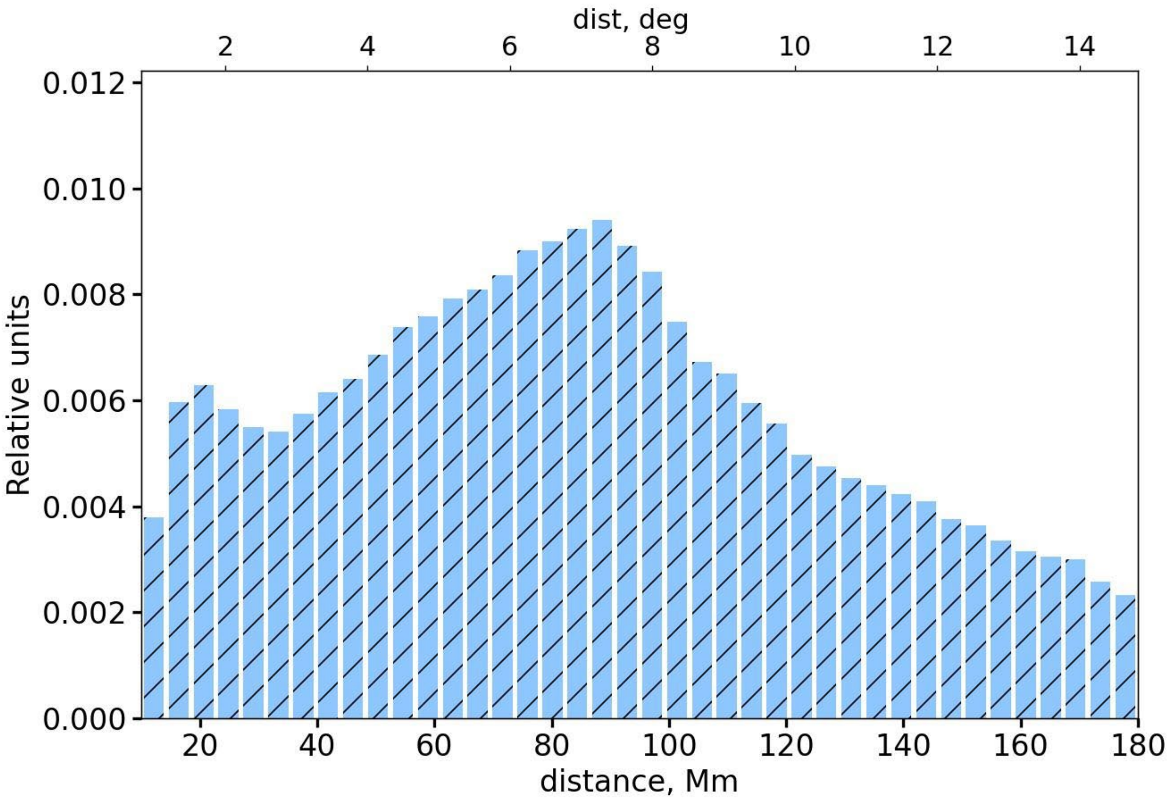
Fig. 3. Variation of the magnetic axis size as a function of the magnetic flux of bipoles.

Fig. 4. Distribution density of the number of bipoles in tilt-angle coordinates of the magnetic axis size of bipoles.



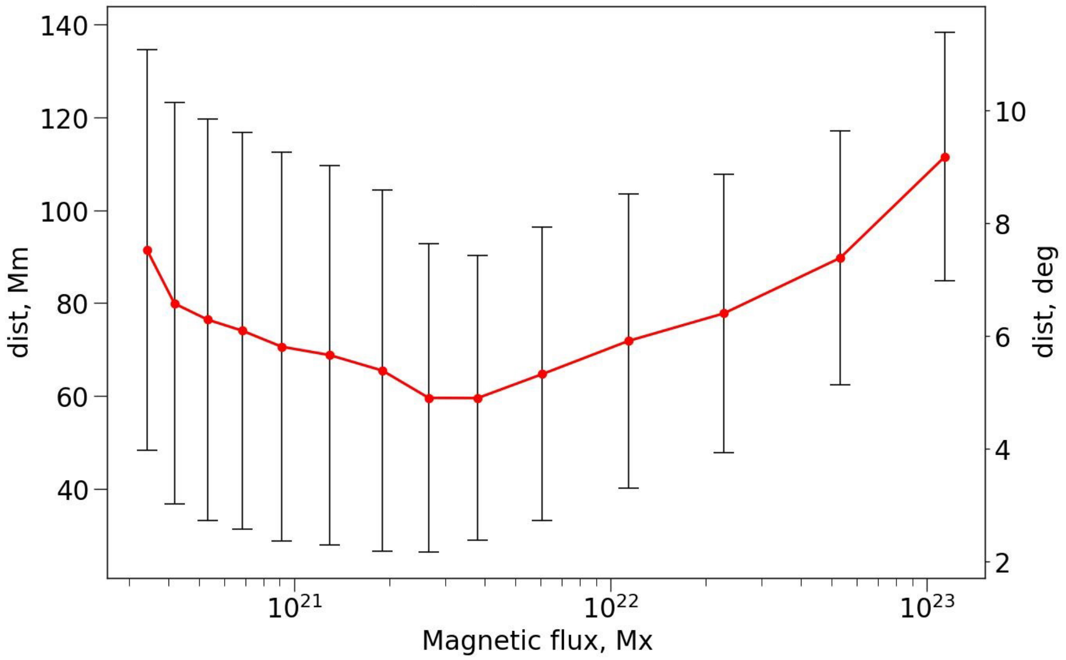
80
60
40
20
0
−20
−40
−60
−80
Latitude
2012
2014
2016
2018
2020
2022
2024
Year
10^0
0
-10^0
Tilt, deg

Fig. 1.



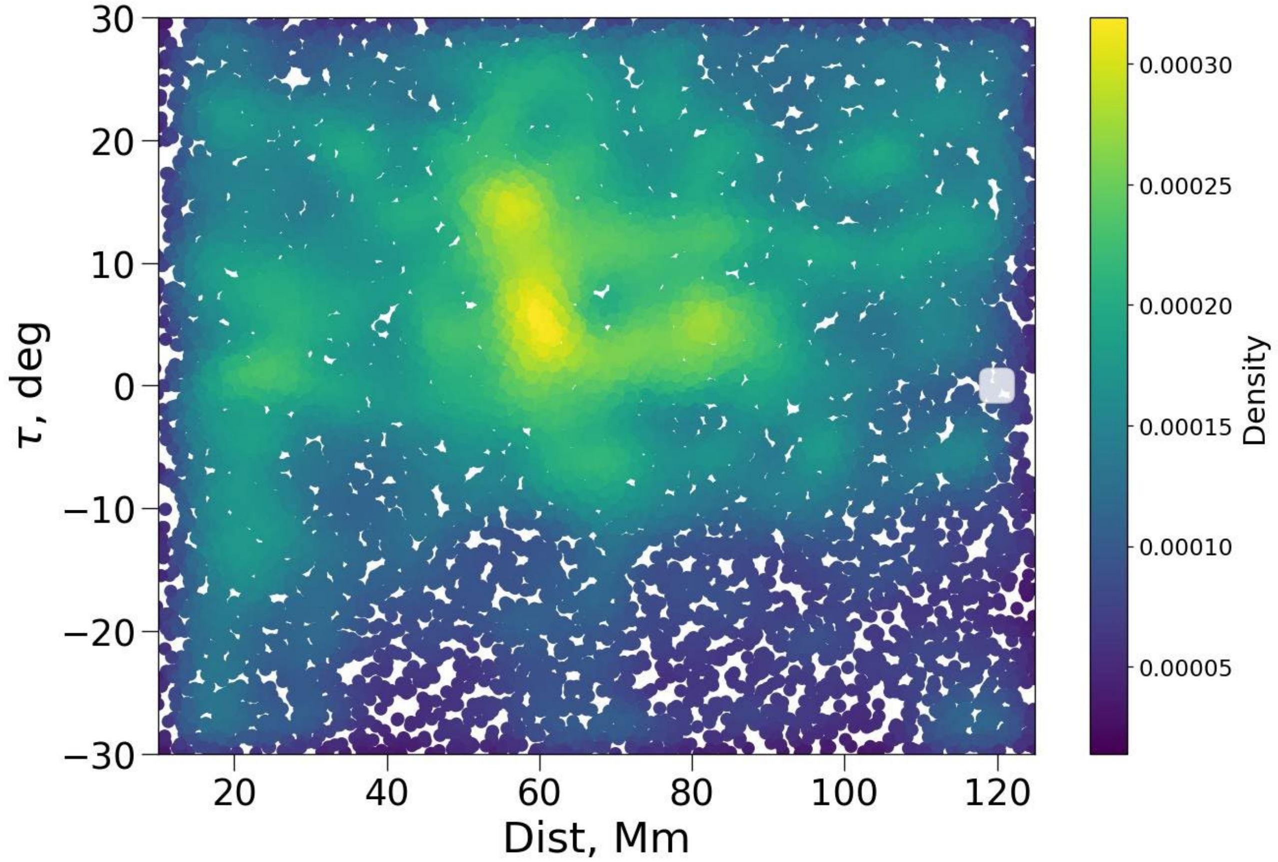
dist, deg
2
4
6
8
10
12
14
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Relative units
20
40
60
80
100
120
140
160
180
distance, Mm

Fig. 2.



140
120
100
80
60
40
dist, Mm
10
8
6
4
2
dist, deg
10^{21}
10^{22}
10^{23}
Magnetic flux, Mx

Fig. 3.



30
20
10
0
−10
−20
−30
τ, deg
20
40
60
80
100
120
Dist, Mm
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
Density

Fig. 4.