



# Lifetime of Sunspots and Pores

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## Abstract

The lifetime of individual sunspots and pores is analyzed according to *Solar Dynamics Observatory/Helioseismic and Magnetic Imager* (SDO/HMI) data from the period 2010–2022. It is found that the lifetime of individual sunspots and pores differs from the Gnevyshev–Waldmeier rule formulated for groups of sunspots. The dependence of the lifetime has a different pattern for different types of spots. For pores, the lifetime does not depend on the polarity of the magnetic field and has a logarithmic dependence on the area  $T_{pr} = 0.24(\pm 0.01) + 0.55(\pm 0.14)\log(S_{mx})$ . For regular sunspots with a developed penumbra, the dependence on the area has a linear form, but depends on the polarity of the magnetic field. For sunspots with a magnetic field of the leading polarity  $T_{ld}^{sp} = -0.62(\pm 0.2) + 0.036(\pm 0.002)S_{mx}$ . For sunspots of trailing polarity  $T_{tr}^{sp} = 0.95(\pm 0.1) + 0.01(\pm 0.001)S_{mx}$ . The decay time and the total lifetime of sunspots is related to the rate of flow in sunspots. The average vertical speed in sunspots decreases with their increasing area. Moreover, the flow rate in the sunspots of the trailing polarity is higher than in the sunspots of the leading polarity. This difference in the velocity explains the difference in the lifetime of the sunspots of the leading and trailing magnetic polarity.

**Keywords** Sunspots · Solar cycle · Solar activities

## 1. Introduction

Groups of sunspots live from a few hours to several months. It is believed that the lifetime of groups increases linearly with the maximum size in accordance with the so-called Gnevyshev–Waldmeier (GW) rule:  $A_0 = WT$ , where  $A_0$  is the maximum area of a sunspots group during its lifetime,  $T$  is its lifetime, and  $W = 10 \mu\text{sh day}^{-1}$  ( $\mu\text{hm}$  micro solar hemisphere). This regularity was first found by Gnevyshev (1938) and mathematically formulated by Waldmeier (1955). According to this rule, most sunspots live less than a day.

The evolution of sunspots is usually divided into two stages: growth and decay. The decay phase is much longer than the growth phase (Howard, 1992; Javaraiah, 2012). Therefore, to a large extent, the lifetime of sunspots is determined by the decay phase. There are different models of the decay of groups of sunspots based on different approximations of the decay

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time. If the rate of decay does not depend on the area, then this will indicate a diffusion process (Krause and Rüdiger, 1975; Stix, 2002). In later studies, it was found that the rate of decay depends on the size, but with different functional forms. Moreno-Insertis and Vazquez (1988) and Petrovay and Van Driel-Gesztelyi (1997) found that the decay rate is proportional to  $A_0^{0.5}$ , which suggests a mechanism of magnetic-field erosion from the edges of sunspots. On the other hand, Howard (1992) and Chapman et al. (2003) found that the decay rate is proportional to the first power of the size of the region [ $A_0$ ]. Bumba (1963) suggested that the decay rate depends on the type of sunspot group. Large groups of sunspots that can be observed over several solar rotations decay slowly. More numerous, small groups of sunspots tend to decay quickly. Nagovitsyn, Ivanov, and Osipova (2019) found that the general Gnevyshev–Waldmeier rule (Gnevyshev, 1938; Waldmeier, 1955) for all groups of lifetime can be written as  $A_0 = 12.1T$ . However, for groups of small-area sunspots, it is slightly different,  $A_0 = 8.02T^{1.105}$ .

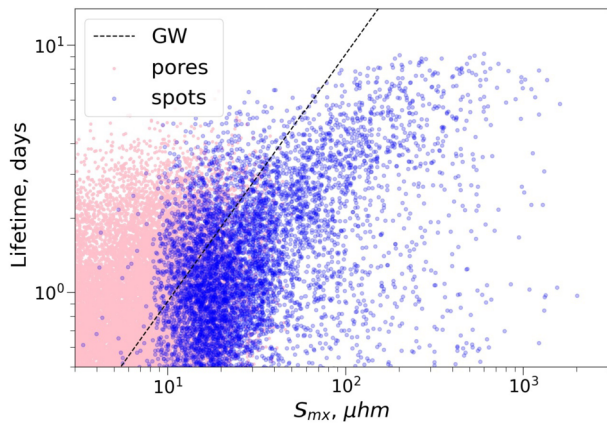
As a rule, the lifetime of sunspots is estimated according to the data of groups of sunspots. Petrovay and Van Driel-Gesztelyi (1997) studied the lifetimes of individual sunspots according to the catalog of the Debrecen (DPR) Observatory for the years 1977–1978. The result of this analysis was the conclusion that the Gnevyshev–Waldmeier rule is also valid for individual sunspots:  $A_0 = 10.89(\pm 0.18)T$ . At the same time, the validity of this conclusion could be influenced by the sampling of the DPR. In particular, the fact that observations of the DPR number are usually separated by one day (and sometimes two–four day) intervals. This is especially critical for determining the lifetime of small sunspots and pores whose lifetime is less than a day. The lifetime of sunspots, determined by ground-based observations, of the order of a day or longer than about a week, is often not very accurately determined due to interruptions in observations due to nightfall or the departure of sunspots beyond the solar limb as a result of the rotation of the Sun. Chapman et al. (2003) analyzed the decay of 32 sunspots and concluded that the decay rate strongly correlates with the total area of the sunspot.

Tlatov and Pevtsov (2014) showed that, according to the properties of the magnetic field, sunspots can be divided into two populations. These populations clarified the classical division of sunspots into pores, that is small spots without penumbra and regular sunspots in which the penumbra is well developed. Tlatov, Riehoainen, and Tlatova (2019), Tlatova et al. (2022) showed that in the distribution of the areas of individual sunspots and pores, individual sunspots and pores present two local maxima. In addition, it is the difference between pores and sunspots that leads to the appearance of two populations in the distribution of the areas of sunspot groups (Dmitrieva, Kopecky, and Kuklin, 1968; Nagovitsyn et al., 2016).

Muraközy (2021), using a sample of 750 groups, showed that the decay rates vary linearly with the maximum area, but may differ with the phase of the solar cycle and latitude. Differences in the rate of magnetic-flux reduction for sunspots of different polarities were also established in the work of Norton et al. (2017). Muraközy (2022) found an asymmetry in a sample of 142 sunspots, depending on the polarity of the magnetic field for the sunspots of the leading and trailing polarity. On the other hand, Plotnikov, Abramenko, and Kutsenko (2023) were unable to detect differences in the decay rate for sunspots of the leading and trailing polarity.

In this article, the aim is to clarify the lifetime of individual sunspots and pores and to determine the factors affecting their lifetime.

**Figure 1** The lifetime of sunspots and pores versus the  $S_{mx}$  area. The dashed line shows the GW dependence for sunspot groups.



## 2. Data

For the analysis, we used *Solar Dynamics Observatory/Helioseismic and Magnetic Imager* (SDO/HMI) data with a cadence of 45 seconds. We processed five images for each day at times close to 00:00, 05:00, 10:00, 15:00, and 20:00 UT. Detection of the boundaries of sunspots, sunspot umbrae, and pores was performed using the procedure for detecting sunspots (Tlatov et al., 2014; Tlatov, 2022b). Magnetic-field intensity and velocity were also determined by superimposing contours on magnetograms and Dopplergrams taken at the same time with SDO/HMI. In total, in the period 2010–2022, more than 155,000 sunspots, 72,909 sunspot umbrae, and 314,060 pores were identified.

## 3. Analysis Results

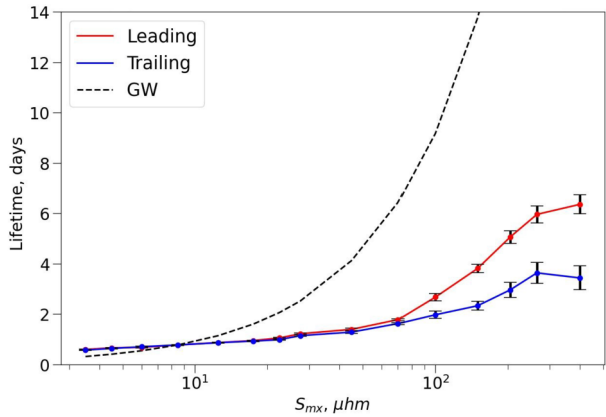
### 3.1. Lifetime of Solar Pores and Sunspots

Tracking occurred when identifying individual sunspots and pores in various images over time. Five images of the photosphere were processed per day. To more accurately identify the sequence of sunspots over time, we took into account the polarity of the magnetic field.

On each image in the continuum, according to the contours of individual sunspots, we determined characteristics such as coordinates and area. Then the contours of the sunspots were transferred to images of the magnetic fields and velocity taken at the same time. Thus, we formed tables of characteristics of sunspots for each moment of time. Then we compared the data obtained on successive images. For each sunspot in a neighboring image, the sunspot closest in coordinates and the same polarity of the magnetic field was searched for. If the distance between the sunspots in the sequence exceeded the critical distance  $d > d_{lim} \approx 1^\circ$  or the areas differed by more than 30%, the sequence was interrupted. The leading or trailing polarity of the sunspots was determined by the Hale magnetic polarity in solar cycles (Hale et al., 1919).

Thus, chains of individual sunspots and pores were formed in time, according to which the analysis of evolution and lifetime was carried out. In total, during the period 2010–2022,  $\approx 33,000$  chains of sunspot sequences were identified. Since we can observe spots only on the visible side of the solar disk, we took sequences of spots in which the longitude of the first spot in the sequence did not exceed  $\phi < -30^\circ$  from the central meridian. This equates

**Figure 2** Approximation of the lifetime lines of pores and sunspots depending on the  $S_{mx}$  area. Approximations are given for the sunspots of the leading and trailing polarities.



to approximately 4.6 days before the disappearance of the sunspot on the western limb. To search for recurrent sunspots, such as those that live more than one rotation, the search was carried out for spots more than  $S_{last} > 100 \mu\text{hm}$ , where  $S_{last}$  is the last recorded area of the sunspot on the visible side of the disk near the western limb.

Figure 1 shows a scatter diagram for the lifetime of pores and sunspots as a function of the  $S_{mx}$  area, where  $S_{mx}$  is the maximum area in the sequence chain. For the area range  $S_{mx} \approx 10 - 20 \mu\text{hm}$ , there is an overlap of the region of the existence of pores and regular sunspots. The diagram also shows the Gnevyshev–Waldmeier dependence line  $A_0 = 10.89T$ . As expected, mostly the sunspot points are below the GW-line for groups of sunspots. This corresponds to a longer lifetime for groups of sunspots than the lifetime of individual sunspots. But the area of the lifetime of the solar pores lies both below and above the GW-line.

Figure 2 shows approximations of the lifetime line depending on the area depending on the logarithm of the  $S_{mx}$  area. Approximations are constructed separately for sunspots of leading and trailing polarity. The approximation line intersects the GW-line in the area of small area sunspots  $S_{mx} \approx 10 \mu\text{hm}$ .

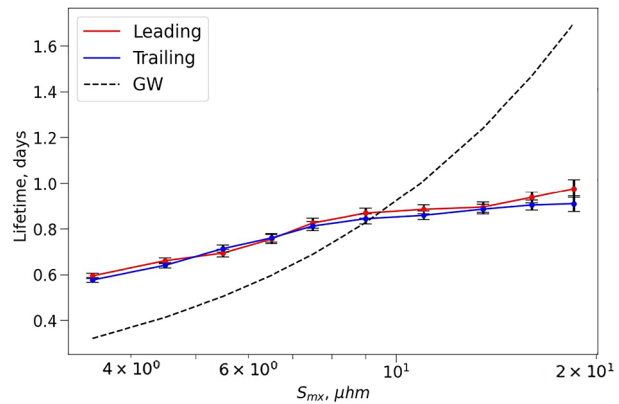
The error range here and in the following figures is the confidence interval  $\sigma/(n + 1)^{0.5}$ , where  $\sigma$  is the dispersion, and  $n$  is the number of elements in the sample in a given area interval.

In Figures 1 and 2, for sunspots with an area of  $S_{mx} > 200 \mu\text{hm}$ , we observe deviations of patterns in the region of shorter lifetimes. This is due to the limitations associated with the inability to accurately track sunspots on the invisible side of the Sun.

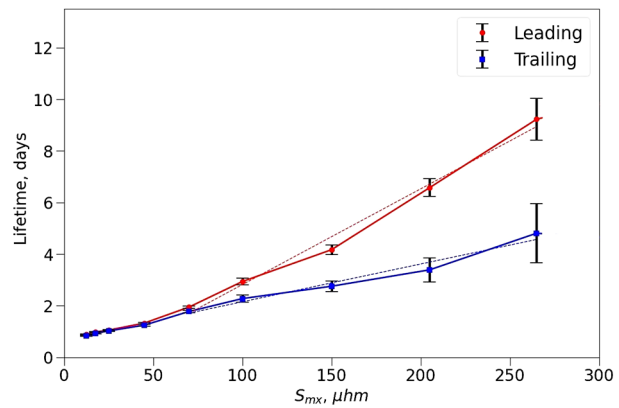
Let us consider the lifetime of the pores in more detail. Figure 3 shows the dependence of the lifetime of pores with a maximum area in the range  $S_{mx} \approx 3 - 20 \mu\text{hm}$ . The lifetime of the pores has a linear dependence on the logarithm of the area,  $T_{pr} = 0.24(\pm 0.01) + 0.55(\pm 0.014)\log(S_{mx})$ , with correlation  $r \approx 0.985$ . The lifetime for these does not depend on the polarity of the magnetic field.

Regular sunspots, that is, sunspots with a developed penumbra, with an area of more than  $S_{mx} > 50 \mu\text{hm}$  have a linear dependence on the  $S_{mx}$  area; see Figure 4. But the approximation differs depending on the magnetic polarity of the sunspots. For sunspots of the leading polarity, the approximation can be expressed by the relation  $T_{ld}^{sp} = -0.62(\pm 0.2) + 0.036(\pm 0.002)S_{mx}$ ,  $r \approx 0.998$ . For sunspots of trailing polarity, the dependence is as follows:  $T_{tr}^{sp} = 0.95(\pm 0.1) + 0.01(\pm 0.001)S_{mx}$ ,  $r \approx 0.99$ . Thus, the lifetime of sunspots of the

**Figure 3** Pore lifetime dependence on the logarithm of the  $S_{mx}$  area. The lifetime of sunspots groups is indicated by the GW-line.



**Figure 4** Lifetime of regular sunspots dependence on the  $S_{mx}$  area for sunspots of the leading and trailing polarity. The dotted lines show a linear approximation.



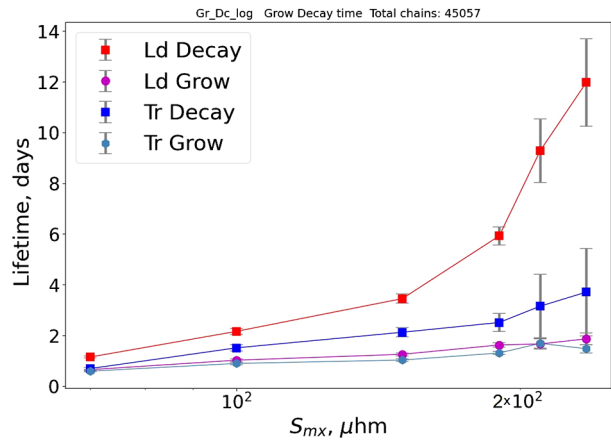
leading polarity with an area of  $S_{mx} > 200 \mu\text{hm}$  is approximately three times longer than for sunspots of the trailing polarity of the magnetic field.

We have determined the time intervals of the growth and decay phases of sunspots in Figure 5. By the growth phase, we mean the time interval from the origin of a sunspot in the form of a pore, until it reaches the maximum area of  $S_{mx}$ . For the decay phase, we considered the time interval from reaching the  $S_{mx}$  area to the last moment of identification of the sunspot. We also divided the sunspots by the polarity of the magnetic field. Figure 5 shows that for relatively large sunspots, the growth phase has a significantly shorter duration than the decay phase. Therefore, for sunspots  $S_{mx} > 100 \mu\text{hm}$  we can assume that the lifetime is determined by the decay phase. The duration of the growth phase practically does not depend on the polarity of the magnetic field. However, the decay phase of sunspots of the leading polarity has a longer duration than for sunspots of the trailing polarity. This difference increases with the increase in the area of sunspots.

### 3.2. The Difference in the Properties of Pores and Sunspots of the Leading and Trailing Polarity

The lifetime of sunspots depends on the polarity of the magnetic field. Let us take a closer look at the differences between the sunspots of the leading and trailing polarity. For the pores, we did not detect any difference in the lifetime, depending on the polarity. However,

**Figure 5** Duration of the phase of growth and decay of sunspots, depending on their area, for sunspots of the leading and trailing polarities.



the number of pores of the trailing polarity prevails over the pores of the leading polarity. The total number of pores for the period 2010–2022 was 18,473 for the pores with the leading polarity of the magnetic field, and 20,574 for the pores of the trailing polarity, that is the difference is  $\approx 11\%$ . At the same time, the number of sunspot umbrae with a magnetic-field polarity corresponding to the polarity of the leading spot in the Hale cycle (22,174) significantly exceeds the number of umbrae with a trailing magnetic-field polarity (12,831) or  $\approx 1.7$  times more. The distribution of the number of umbrae of the trailing polarity monotonically decreases with the area (Figure 6). For umbrae of the leading polarity in the distribution, there is a local maximum for umbra with an area of  $S_{mx}^{um} \approx 17 - 20 \mu\text{hm}$ .

It is known that the maximum intensity of the  $B_{mx}$  magnetic field in sunspots increases with increasing area (Houtgast and van Sluifers, 1948). Ringnes and Jensen (1960) found a strong correlation between the logarithm of the area and the intensity of the magnetic field. Tlatov and Pevtsov (2014) found  $\log(B_{mx}) = 2.96 + 0.137 \log(S)$ .

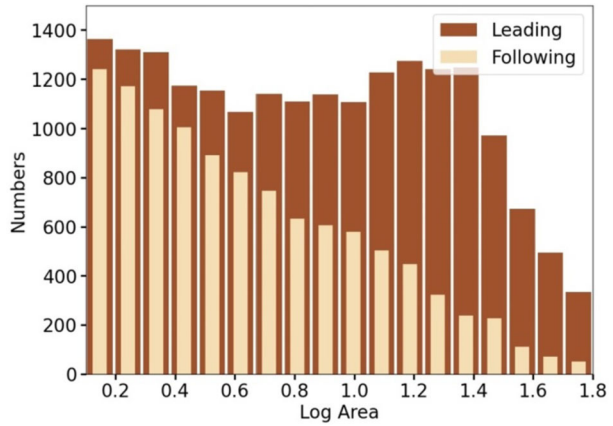
Figure 7 shows the relationship between the logarithm of the area of sunspots and pores  $S$  and the maximum intensity of the magnetic field  $B_{mx}$ . For the construction (Figure 7), we used pores and sunspots in the central zone  $R < 0.5$ . The relationship turned out to be not monotonic; it can be divided into two sections. For sunspots with an area greater than  $S > 100 \mu\text{hm}$ , they are linearly related to the logarithm of the area:  $B_{mx}^{sp} = 615.4(\pm 19.9) + 442.6(\pm 8.5)\log(S)$ ,  $r \approx 0.98$ . However, for small sunspots ( $S < 50 \mu\text{hm}$ ) and pores, the  $B_{mx}$ -dependence on the area is absent; remaining approximately constant  $B_{mx} \approx 1300 \text{ G}$ .

For the average intensity of the magnetic field [ $B_{av}$ ], the dependence on the area is completely different (Figure 8). For small-area sunspots  $S < 100 \mu\text{hm}$ , the average magnetic field decreases with increasing area:  $B_{av}^{sp} = 1108.7(\pm 8.4) - 265.4(\pm 4.9)\log(S)$ ,  $r \approx 0.99$ . For large-area sunspots  $S > 100 \mu\text{hm}$ , the average field remains almost constant:  $B_{av}^{sp} \approx 530 \text{ G}$ . This is due to the fact that the penumbra makes the greatest contribution to the area of large sunspots.

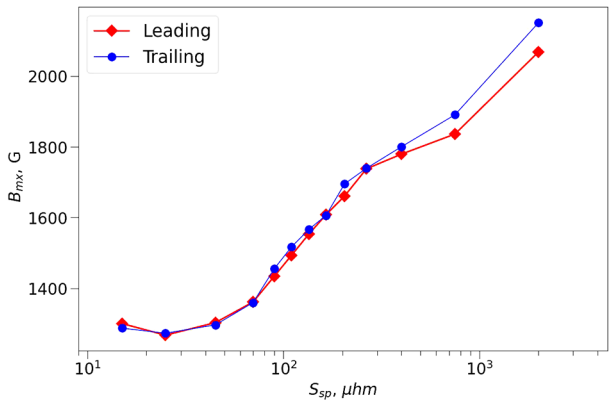
The dependence of  $B_{mx}$  and  $B_{av}$  on the area does not actually depend on the polarity of the magnetic field (Figures 7, 8).

Consider the fraction of the area occupied by umbra [ $S^{um}$ ] in the total area of a sunspot  $S^{sp}$ . Figure 9 shows the dependence of the  $S^{um}/S^{sp}$  ratio on the area for sunspots of the leading and trailing polarity of the magnetic field. For sunspots of the trailing polarity, the proportion of umbra in the area is 15–25% less than for sunspots of the leading polarity. Near the values of the sunspot area  $S^{sp} \approx 100 \mu\text{hm}$ , there is a local maximum of the relative fraction of the area of the umbra.

**Figure 6** Distribution of the number of umbrae with the logarithm of  $S_{um}$  area [ $\mu\text{hm}$ ] separately for magnetic field of the leading and trailing polarity.



**Figure 7** The relationship between the maximum intensity of the magnetic field [ $B_{mx}$ ] and the logarithm of the area for sunspots of the leading and trailing polarity.



**Figure 8** The relationship between the average intensity of the magnetic field [ $B_{av}$ ] and the area for sunspots of the leading and trailing polarity.

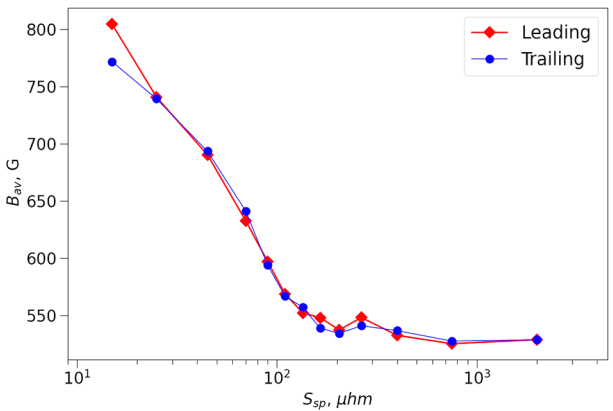
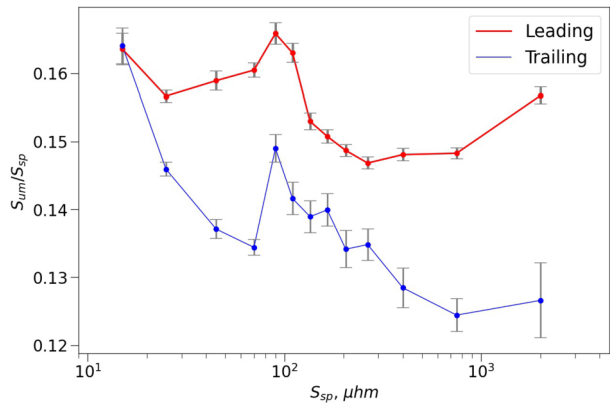


Table 1 shows the values of approximations of lifetime and magnetic fields from the area for various types of sunspots.

**Figure 9** The ratio of the area of the umbra to the total area of the sunspots  $S^{um}/S^{SP}$ , for the sunspots of the leading and trailing polarities.



**Table 1** Summary of lifetime and values of magnetic fields.

Lifetime	
Pores	$T_{pr} = 0.24(\pm 0.01) + 0.55(\pm 0.014)\log(S_{mx})$
Leading	$T_{ld}^{SP} = -0.62(\pm 0.2) + 0.036(\pm 0.002)S_{mx}$
Trailing	$T_{tr}^{SP} = 0.95(\pm 0.1) + 0.01(\pm 0.001)S_{mx}$
Magnetic fields in sunspots	
$S < 50 \mu\text{hm}$	$B_{mx} \approx 1300$
$S > 100 \mu\text{hm}$	$B_{mx}^{SP} = 615.4(\pm 19.9) + 442.6(\pm 8.5)\log(S)$
$S < 100 \mu\text{hm}$	$B_{av}^{SP} = 1108.7(\pm 8.4) - 265.4(\pm 4.9)\log(S)$
$S > 100 \mu\text{hm}$	$B_{av}^{SP} \approx 530$

### 4. Discussion

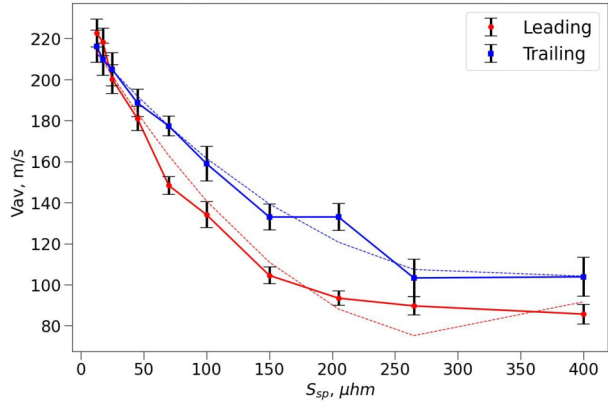
Describing the decay of sunspots remains a problem of solar physics. The study of the decay of sunspots predicts the time frame of magnetic diffusion and may give important limitations on dynamo models. However, studies of the decay of individual sunspots are mainly based on small samples. Long-term research focuses mainly on the decay of groups of sunspots.

Our analysis showed that the decay rate of individual regular sunspots is close to a linear dependence on the area, but this dependence depends on the polarity of the magnetic field in the sunspots (Figure 4). Sunspots of the trailing polarity decay faster (Figure 5). At the same time, the maximum intensity of the magnetic field in  $B_{mx}$  sunspots and the average magnetic field [ $B_{av}$ ] do not depend on the type of sunspots, but only on the area (Figures 7, 8). These findings cast doubt on the results of the study of Martínez Pillet, Moreno-Insertis, and Vazquez (1993) on the nonlinear dependence of the decay rate of sunspots, depending on the intensity of the magnetic field, as well as on a model of turbulent erosion (Petrovay and Van Driel-Gesztelyi, 1997), which assumes a variable diffusion capacity depending on the magnetic field. This means that the mechanism of the decay of sunspots remains not fully understood.

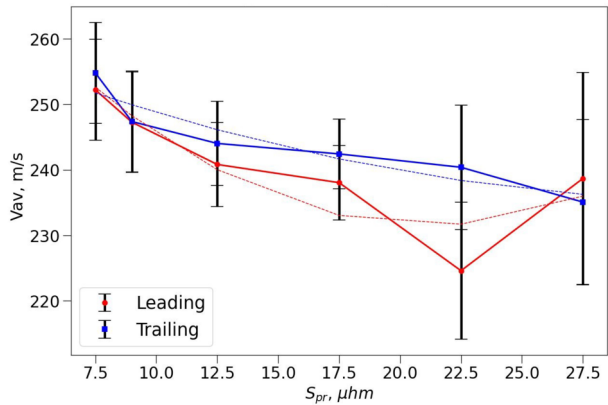
For sunspots, the decay time should be related to the size of the sunspots by the ratio  $\Delta S/\Delta t \approx \text{const.}$  or  $\Delta r/\Delta t \sim 1/r$ , where  $r$  is the radius of the sunspot,  $t$  is the lifetime of sunspot with an area of  $S$ . Convection may play a crucial role in the mechanism of sunspot decay. A similar decay model was proposed by Simon and Leighton (1964). In this model,



**Figure 10** Vertical velocity of the flow depending on the area for sunspots of the leading and trailing polarity.



**Figure 11** The vertical velocity of the flow in solar pores of the leading and trailing polarity, depending on the area.



the bits of the magnetic field are cut off from the edge of the sunspot and swept away by supergranular flows to the boundaries of supergranular cells. The basis for the hypothesis of Simon and Leighton (1964) is turbulent diffusion. But then the decay rate should not depend on the size of the sunspots.

We can assume that the decay rate is proportional to the convective energy density  $\Delta r/\Delta t \sim E_{con} \sim \rho v^2$ , where  $v$  is the velocity of convective flows. We can test this hypothesis. In our sunspot-segmentation algorithm, we can highlight boundaries. We superimposed the selected contours on the maps of Doppler velocities according to SDO/HMI data obtained at the same time.

Previously, differential rotation was subtracted from the SDO/HMI maps (Beck, 2000). After that, a constant component of the velocity was subtracted from each image of the Doppler velocity. Thus, the average velocity in the central part of the Sun’s disk was reduced to zero.

For comparison, we used daily series of observations made in the period 2010–2022 at 05:00 UT. To determine the velocity, we took sunspots in the central zone located at a distance of  $r < 0.5R_{\odot}$ . Thus, we measured close to the vertical velocities along the line of sight in the sunspots.

Figure 10 shows the dependence of the average vertical velocities in sunspots depending on the area. For small sunspots, the velocity reaches values of  $V = V_{\text{av}} \approx 220 \text{ m s}^{-1}$ , while for large sunspots, the velocity drops to  $V \approx 80 - 100 \text{ m s}^{-1}$ .

The change in the vertical velocity with a change in area can be approximated for sunspots of the leading polarity as  $V^{\text{ld}} \approx 493S^{-0.29} \text{ m s}^{-1}$ ; for sunspots of the trailing polarity  $V^{\text{tr}} \approx 386S^{-0.21} \text{ m s}^{-1}$ , and for all sunspots as  $V \approx 450S^{-0.27} \text{ m s}^{-1}$ . Hence, the dependence of the velocity on the radius of the sunspots can be roughly represented by  $V \sim 1/r^{0.5}$ . It can be noted that the convective energy density  $[E_{\text{con}}]$  is proportional to  $1/r$ . The decay rate of sunspots is also  $\Delta r/\Delta t \sim 1/r$ . Perhaps these two parameters are interrelated and can be used in the construction of models of the decay of sunspots.

As we can see from Figure 10, the velocity  $[V]$  for sunspots of the trailing polarity is greater than for sunspots of the leading polarity of the same area (Figure 10). Therefore, if our hypothesis is correct, then the rate of decay of sunspots of the trailing polarity should be higher. This is what we see in Figures 4 and 5. Thus, the flow has a decisive effect on the decay time of sunspots. Note that higher values of the flow velocity for the trailing sunspots lead to a greater Coriolis force deflecting the sunspots toward the poles, and therefore can affect the magnitude of the tilts of the angles of the solar bipoles.

For solar pores, the vertical velocity practically does not change with the change in area (Figure 11). Perhaps, for the pores the mechanism of decay is different. This may be an effect of the heating from the surrounding undisturbed gas. In this case, Newton's formula can be applied to equalize the temperature,  $\Delta T_{\text{pr}}/\Delta t \sim (\tau_{\text{ph}} - \tau_{\text{pr}})$ , where  $\tau_{\text{pr}}$  is the pore temperature and  $\tau_{\text{ph}}$  is the temperature of the unperturbed photosphere. Then the lifetime of the pores will be proportional to the logarithm of the temperature difference,  $T_{\text{pr}} \sim \log(\tau_{\text{ph}} - \tau_{\text{pr}})$ . The pore temperature is directly related to the relative contrast, and in turn to these areas (Tlatov, 2022a). Thus, it is possible to substantiate the logarithmic law of the lifetime of pores by the heating mechanism.

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**Data Availability** All data used are available at the HMI JSOC.

## Declarations

**Competing interests** The author declares no competing interests.

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