Dark Dots on the Photosphere and Their Counting in the Sunspot Index

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Abstract
A large number of small dark areas can be observed in the continuum with high-spatial resolution in recent satellite observations of the Sun, as well as in high-quality ground-based data. These regions have no penumbra, have a contrast of up to 20% and are similar to solar pores. The characteristic area of such structures is from 0.3 to 5 µhm or from 0.5 to 7 Mm typical diameter. The number of such points in one image can be several hundred. The nature of such formations remains unclear.

We have performed a selection of dark regions with a contrast of at least 3% of the level of the quiet Sun using data obtained with the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO) from 2010 to 2020. We have studied the properties of “dark dots”, including their variation with the solar cycle, area distribution, and contrast. We also studied the intensity of the magnetic field of such structures. We found that the number of dark dots with an area of less than 5 µhm, in which the magnetic field is not significant and is less than $|B| < 30$ G, is from 60 to 80% of the total number of structures of this size. This means that they are not associated with magnetic activity. The existence of such structures can significantly affect the calculations of the sunspot index since they can be mistaken with pores.

Keywords Sunspots · Magnetic fields · Active regions · Structure

1. Introduction

Sunspots appear on the photosphere as regions with reduced temperature and radiation. A sunspot looks like a part of the photosphere with significantly less brightness than the surrounding areas. Regular sunspots consist of a dark umbra surrounded by a lighter penumbra. In the transition from umbra to penumbra and photosphere, the intensity of the radiation changes abruptly. Inside the penumbra, the intensity is approximately constant; inside the umbra, as a rule, it decreases towards the center. The umbra, on average, occupies 15 – 25% of the sunspot area. The brightness of the umbra is 5 – 15% of the brightness of the photosphere but does not depend on the size of the umbra (Vitinsky, Kopecky, and Kuklin, 1986).
In addition to regular sunspots, there are pores and transitional spots (Vitinsky, Kopecky, and Kuklin, 1986; Tlatov and Pevtsov, 2014). Small sunspots that do not have a penumbra are called pores. Its size ranges from $1''$ to $5''$ or $\approx 0.7-3.5$ Mm, which corresponds to an area of $\approx 0.4-4$ µhm (Vitinsky, Kopecky, and Kuklin, 1986). Pores are found both as individual formations and as part of groups of sunspots. The lifetime of the pores is several hours, but as part of a group, these can exist for up to several days, according to the observations of the Kislovodsk Mountain Astronomical Station of the Pulkovo Observatory (KMAS).

The maximum value of the area distribution is $S_{por} \approx 3.6$ µhm for pores and $S_{sp} \approx 120$ µhm ($d \approx 30''$) for regular sunspots (Tlatov, Riehokainen, and Tlatova, 2019). Transitional sunspots, as a rule, have an area in the range of $20-100$ µhm and are located in between the pores and regular sunspots since the penumbra of these is not fully formed (Tlatov and Pevtsov, 2014; Tlatov, Riehokainen, and Tlatova, 2019).

The sunspot index $Ri$ counts sunspots and pores (Clette et al., 2014; Svalgaard and Schatten, 2016). Currently, it is necessary to limit the size of small dark structures, especially with an automatic detection method. For ground-based observations obtained during the 19th and the early 20th centuries, such a restriction was natural, since small aperture telescopes were used, and the observation conditions did not allow observing with a spatial resolution better than $2''-4''$. However, recently, due to the start of observations obtained on board spacecraft, as well as ground-based observations from telescopes with a relatively large aperture and registration on CCD detectors with a short exposure time, it has become possible to register a structure of the order of $1''$ or less.

In this work, we have performed the selection of dark structures in the photosphere according to the observations of SDO/HMI for the period 2010–2021. A large number of such structures are not associated with magnetic activity. Consequently, this may introduce errors in the calculation of the sunspot index.

2. Data and Data Processing

2.1. Differences in Sunspot Data

Small-area groups and spots account for a significant part in the calculations of sunspot indices. Figure 1 shows histograms of the distribution of the areas of sunspot groups according to the data of the Debrecen1 and Kislovodsk2Observatories for the period 1974–2018. The maximum value of the distribution of the area of Debrecen happens in groups with an area of $2-3$ µhm. The percentage of groups with an area of $S < 5$ µhm in the total number is $\approx 25\%$. In the Kislovodsk data, the maximum area distribution is $8-10$ µhm, and the proportion of groups with an area of $S < 5$ µhm is less than $3\%$.

The difference is significant. The data used by Debrecen Observatory were both its own and observations of Kislovodsk and other ground-based and satellite observatories. Both observatories use automatic sunspot recognition techniques (Baranyi et al., 2001; Tlatov et al., 2014). In Kislovodsk, spots with an area less than 2 µhm are not taken into account. Therefore, the proportion of sunspots and small-area groups in Kislovodsk is significantly less than in the Debrecen data. But the question is, how justifiable is the choice of the lower threshold of the area $S_{min} > 2$ µhm.

1http://fenyi.solarobs.csfk.mta.hu.
2http://www.solarstation.ru.
Figure 1 Distribution of the area of groups of sunspots for $S_{gr} < 60$ µhm according to the data of Debrecen (a) and Kislovodsk (b).

Figure 2 Contrast of pores (a) and spots (b) according to Kislovodsk data in Cycle 24 depending on the logarithm of the area.

We have performed the analysis of the continuum images obtained with the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamicis Observatory (SDO). The choice of such data from the space observatory provided high-quality images without the influence of the atmosphere. For the analysis, we used data from 01 May 2010 to 23 September 2021 with an exposure of 45 seconds at a time close to 5:00 UT. The magnetic field data were selected for the same time in order to most accurately combine measurements in the continuum with observations of magnetic fields.

For a comparative analysis of the characteristics of dark features, it is necessary to know the typical contrast distribution for sunspots and pores. Observations of sunspots have been carried out at the Kislovodsk station since 1947. Since 2010, observations have been carried out on digital receivers. Detection of sunspots, sunspot umbrae, and pores is carried out using a computer program in semi-automatic mode. In this case, the operator can change the conditions for selecting objects, which ensures the best accuracy (Tlatov et al., 2014).

According to Tlatov, Riehokainen, and Tlatova (2019), we present the characteristics of pores and spots according to KMAS observations. We used this series to determine typical contrast values. Figure 2 shows the contrast of pores and sunspots (with penumbrae) de-
pending on the area. The contrast was calculated as the ratio of the minimum brightness in
the feature relative to the brightness of the outer border. The brightness of the photosphere
surrounding the object is taken as the value 1. The pore contrast ranges from a few percent
to 20–40% (Figure 2a). The contrast of the spots can reach a much larger value (Figure 2b).
Thus, to detect pores and other dark features, it is necessary to select those with a contrast
of at least several percent of the level of the undisturbed photosphere.

To detect dark dots on SDO/HMI images, it is necessary to remove the darkening to-
wards the limb and other possible intensity inhomogeneities on the disk. The procedure for
eliminating the darkening to the limb and determining the background intensity of \( I_{bg} \) was
as follows. The disk of the Sun was divided into 12 portions or segments of 30° degrees
each. Inside each segment \( k \), the intensity change function from the radius \( R_k = f(i) \) was
determined, where \( i \) is the pixel number from the center of the disk. In the center of the
disk, for a circle of radius \( R_c = 0.3R_{\odot} \), the maximum intensity distribution \( I_c \) was
Calculated. For distances \( r > R_c \), the background intensity was determined by interpolation
\( I_{bg}(r, \alpha) = I_k(r) + a + b \), where the values of \( a \) and \( b \) were calculated depending on the
angle \( \alpha \) located between the centers of the segments \( k \) and \( k + 1 \). For distances \( r < R_c \), the
background value was calculated as \( I_{bg}(r, \alpha) = I_c + dI(r, \alpha) \). The procedure was repeated
twice. If, at a distance \( r \), there were regions of brightness exceeding 5% of the average
value, then at the second step, they were excluded, and the procedure was repeated. Then,
the intensity was recalculated in comparison to the intensity at the center of the solar disk \( I_c \).
To do this, the intensity of each pixel \( (i, j) \) was calculated as \( I'_{c}(i, j) = I_c - (I'_{o,j} + I'_{bg}(i, j)) \), where
\( I_{o,j} \) and \( I_{bg}(i, j) \) correspond to the initial and modified intensities. This procedure makes it
possible to eliminate darkening to the solar limb and to take into account large-scale intensity
inhomogeneities across the disk.

The procedure for selecting regions was as follows. A point with a minimum intensity
was selected on the solar disk \( (i, j) \). The intensity did not exceed the average intensity
\( I_{i,j} < 0.97I_c \). Next, we applied the growing procedure. In the vicinity of the point \( (i, j) \), we
found the intensity of the maximum of the distribution \( I_{md} \) and the standard deviation \( \sigma \).
Next, we applied the growing procedure. To do this, we divided the intensity into intervals,
with a step \( \Delta I = 0.5\sigma \). Further from the pixel \( (i, j) \), we increased the area in the intensity
range from \( I_{i,j} \) to \( I_{i,j} + \Delta I \). We attached pixels from the borders of the selected range
to the already selected pixels. Then we increased the upper limit of the intensity range by
\( \Delta I \) and repeated the procedure. To speed up the procedure, not all pixels were searched, but
only those bordering the selected ones that were not yet included in the group. At each step
\( k \) of the intensity range \( I_k = I_{i,j} + k \cdot \Delta I \), we calculated the growth rate of the region by
the number of newly attached points compared with the number of points in the previous
step. With an increase in the number of points \( \Delta N = (N_k - N_{k-1})/(N_{k-1} + N_{min}) > 0.8 \),
the growing procedure stops. Here \( N_{min} \) is the number of minimum of pixels peculiar to the
sunspot; in our case, this size was determined from the minimum area of \( S_{min} \approx 2 \mu m^2 \). Pixels
attached at the last step \( k \) : \( \Delta N > 0.8 \) were discarded. The pixels attached at steps 1
to \( k - 1 \) remain in the selected region. This procedure allows us to track the intensity of the
boundary of the region \( I_{rg} \). Since the rapid growth of the region at step \( k \) means a transition
in intensity from the local region to background values. Moreover, this \( I_{rg} \) value can vary for
different regions of the Sun’s disk. This means that instead of some fixed threshold intensity
level for the entire disk, we selected a local threshold level specific to that part of the disk.
In future steps, we marked all the selected points of this region as already processed and
excluded them from the further search procedure.

After that, we again looked for points of minimum intensity and repeated the growing
procedure. Sometimes two grown areas may touch borders. In this case, we combined them
into one region.
Various parameters were determined for each region, including coordinates, area, average contrast, and other cluster parameters. The magnetic field was also measured.

Figure 3 shows images of a part of the solar disk in intensity and magnetic field for SDO/HMI on 4 July 2010 at 5:00 UT. In the figure, we have indicated dark regions for which there is no increase in the intensity of the magnetic field. There can be quite a lot of these regions on the disk.

### 2.2. Data Processing Results

Figure 4 shows the average monthly values of the number and area of selected dark regions. The area of dark regions is maximal in the epoch of maximum activity and is close to the area of sunspots measured in Kislovodsk. We have identified structures in which the average magnetic field $B_{av}$ in absolute value is less than 30 G and more than 100 G. These threshold values were chosen based on the magnitude of the average magnetic fields in sunspots and pores (Tlatov and Pevtsov, 2014). If the total number of dark areas with a significant magnetic field is 40–60 in the epoch of maximum, then the number of areas in which the magnetic field is small is 100–120 and varies slightly with the phase of activity. More precisely, their number is in antiphase with the number of regions having a significant magnetic field. It is probably due to the fact that at the maximum of activity, the area occupied by active regions in which magnetic fields are significant is growing. In this case, there is less space for the existence of black dots.

The area of dark regions detected from SDO/HMI data by the fully automatic method is close to the area of sunspots measured in Kislovodsk. The differences in the areas in the maxima of 2013 and 2014 are associated with omissions in ground observations and a better accounting of the areas of large sunspots near the limb from satellite observations.
Figure 4  Monthly average values of the selected dark structures: number (top) and area (bottom). The results depend on the size and intensity of the magnetic field.

Figure 5 shows summary synoptic maps of dark elements for those with strong and weak magnetic fields for 2017. The distribution with strong magnetic fields corresponds to the localization of active regions. Dark regions with weak magnetic fields evenly fill all longitudes and reach a latitude of $\approx 60^\circ$.

In our analysis, the contrast of detected dark areas exceeded 3%. Figure 6 shows the dependences of contrast and maximum values of the magnetic field inside the region, $B_{\text{max}}$, separately near active regions (ARs) and outside them. To separate the regions, we considered that if the dark region was located at a distance of fewer than 8 degrees in longitude and 5 degrees in latitude from the center of the sunspot group measured in Kislovodsk, then this region is connected by ARs. These sizes roughly correspond to the largest AR in Cycle 24, so if the distance is more than these values, then the region is outside the AR.

Figure 6 shows two ranges of values for the magnetic field in the contrast range of 3–20%. The regions in which the magnetic field reaches 300–500 G are obviously related to the magnetic fields of ARs. However, there are also quite a large number of dark regions in which the contrast is significant, and the magnetic field is not significant. For contrast values of $\approx 15\%$, there is a local maximum in the distribution of the number of regions. With the increase in the area of dark regions that are located near ARs, the contrast increases. Outside ARs, the contrast is weakly dependent on the area (Figure 7).
Figure 5  Distribution of dark areas on the summary synoptic map for 2017. a) For elements in which the magnetic field $|B_{av}| > 100$ G. b) For elements in which the magnetic field $|B_{av}| < 30$ G. Red color corresponds to regions with a positive magnetic field sign, blue with a negative one.

Figure 6  The relationship between the contrast of dark areas and the intensity of the magnetic field: a) In ARs and b) outside ARs.

The distribution of dark regions in function of the logarithm of the area is shown in Figure 8. The maximum value of the distribution of areas with a strong magnetic field is $\approx 1.2 - 1.5 \mu m$. For regions with a weak magnetic field, the maximum is $\approx 1 \mu m$.

The distribution of the magnitude of the $B_{mx}$ magnetic field from the logarithm of the area is shown in Figure 9. For areas in which $B_{mx} > 500$ G, there is an increase in the intensity of the magnetic field with increasing area. This corresponds to the regularities of
the magnetic fields of regular sunspots (Tlatov and Pevtsov, 2014). But there are also regions for which the magnetic field is small. For these, there is no change in the magnetic field with increasing area.

3. Discussion

We detected dark regions on the photosphere based on observations in the SDO/HMI continuum. We used an automatic method of selecting such structures (Section 2.2). The use of SDO/HMI data made it possible to combine observations in “white” light with measurements of magnetic fields. This made it possible to establish that some of the dark regions do not have a significant magnetic field characteristic of sunspots and pores (Tlatov and Pevtsov, 2014).

The area of the selected dark regions, according to SDO/HMI data, in which the magnetic field has large values, turned out to be close to the area of the spots detected at the KMAS observatory (Figure 4). It indicates the validity of the applied algorithm for spot detection.
Figure 9  The relationship between the intensity of the magnetic field $B_{mx}$ and the logarithm of the area of dark regions.

Figure 10  The proportion of dark regions with a magnetic field $B_{av} > 100$ G from the total amount, depending on the area in $\mu$hm.

Our analysis showed that the selection of dark regions on the photosphere in the continuum can lead to an erroneous interpretation of the magnetic activity of the Sun. Indeed, a large proportion of such small-sized regions are not associated with a measurable magnetic field. Figure 10 shows the proportion of dark regions having a significant magnetic field $B > 100$ G to the total number of detected regions. For regions with an area of less than $\approx 4–5$ $\mu$hm, the proportion of regions with an insignificant magnetic field may be significant. Thus, for regions with an area of less than 3 $\mu$hm, the number of regions not associated with strong magnetic fields is more than 80% (Figure 10).

In the article by Tlatov, Riehokainen, and Tlatova (2019), using KMAS data, the characteristic pore area was determined as $S_{por} \approx 4$ $\mu$hm. Our analysis showed that about 80% of dark regions with this area have a significant magnetic field. However, according to the data of the Debrecen Observatory (Baranyi et al., 2001), the maximum value of the distribution of the area of sunspot groups corresponds to 2 $\mu$hm (see Figure 1). But according to the analysis presented here, more than 80% of such spots are not associated with a measurable magnetic field. That is probably why the total number of spot groups in Debrecen is more than 2 times the number of spot groups in Kislovodsk, although the areas of sunspot groups are approximately equal (Baranyi, 2018).
Thus, caution should be taken when assigning small dark regions to the manifestation of solar activity. It may be necessary to limit the pore size in calculating the sunspot index. For single pores, this size should be limited to $S_{\text{min}} \approx 4 \mu \text{m}$ (see Figure 10). Figure 6 and Figure 9 show that small regions without a measurable field can exist not only far away but also near ARs. The area of such regions is usually up to $S_{\text{min}} \approx 2 – 3 \mu \text{m}$. Therefore, with less than this value, they should not be taken into account in calculating the sunspot index.

Another method is the detection of pores using observations of magnetic fields, as is done in this work. But this method significantly limits the use of simple photoheliographs. Another verification method may be to take into account small pores, only near already existing groups of sunspots or faculae visible in white light. We can also take into account the lifetime and latitude for sampling sunspots and pores.

4. Conclusion

We performed an analysis of dark elements present in the continuum according to SDO/HMI observations and compared these elements with the magnetic field measured at the same time. We found that on the images of the Sun’s disk, there are quite a lot ($\approx 100$) elements with an area of $0.3 – 5 \mu \text{m}$ (or a diameter of $0.5 – 7 \text{Mm}$) with a contrast of $\approx 3 – 20\%$, having weak magnetic fields and, apparently, not related to magnetic activity. These regions, which can be called “black dots”, can be mistaken with solar pores in which the intensity of the magnetic field exceeds several hundred Gauss (Tlatov and Pevtsov, 2014). The number of black dots decreases at the maximum of activity and increases at the epoch of the minimum of activity. The black dots are evenly distributed in longitude and are located in the mid-latitude zone up to latitudes $50^\circ – 60^\circ$.

The existence of black dots should be taken into account when calculating the sunspot index since they can be falsely mistaken with solar pores. It is especially important when analyzing images with good spatial resolution, such as satellite observations and observations at high-altitude observatories. The counting into the sunspot index using such images, especially with the use of automatic processing methods, can significantly affect the stability of the sunspot index series.

The criteria should be adapted in case of automatic segmentation of sunspots on high-resolution images. Probably, single pores should not be considered if their sizes are less than $4 \mu \text{m}$. When observing near the limb, small pores, including clusters, should not be taken into account if they exist without accompanying faculae. The counted pores should be limited to an area of $\approx 2 \mu \text{m}$.

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Data Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Disclosure of Potential Conflict of Interest The author declares no conflict of interest.

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