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Variations of Umbral Magnetic Field Strength with Umbral Area, Brightness, and Sunspot Number

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Abstract

Sunspots are regions on the Sun where the magnetic field is highly concentrated. The magnetic field drives the physical conditions within and around sunspots. The study of the relationship between the magnetic field strength in the sunspot umbra and the umbral area, umbral brightness and sunspot number (SSN) provides important information about the physical properties of sunspots and the overall structure of the Sun. In this study, we analyzed high-resolution sunspot images obtained from the Big Bear Solar Observatory (BBSO)/Goode Solar Telescope (GST) for 2015 - 2022 time intervals. The corresponding daily sunspot number (SSN) data were taken from the Solar Influences Data Analysis Center (SIDC) website, and the magnetic field measurements were obtained from the GST/Near InfraRed Imaging Spectropolarimeter (NIRIS). The variations of the mean umbral magnetic field intensity with respect to the umbral area, umbral brightness, and SSN were investigated, and Pearson correlation analysis was performed to explore the relationships between them. Our analysis revealed the following results: i) There is a power-law relationship between the mean umbral area and the magnetic field strength and the magnetic field strength increases with increasing umbral area. ii) The magnetic field strength decreases with increasing mean umbral brightness. iii) A weak relationship was found between the umbral magnetic field strength and the SSN.

Keywords: sunspot; umbral area; umbral magnetic field; sunspot number

1. Introduction

Solar magnetic fields are generated by the motion of electrically charged ions and electrons within the solar plasma (Hale 1908; Hale et al. 1919). These magnetic fields play a crucial role in the formation of sunspots and are directly linked to the operation of the solar dynamo (Hale et al. 1919; Charbonneau 2020; Fan 2021). Therefore, studying the magnetic field of sunspots provides valuable insights into the underlying physical processes driving solar activity.

Sunspots are temporary dark areas on the surface of the Sun due to their low temperature compared to their surroundings. Sunspots have very strong magnetic fields and the magnetic field in these structures is on average on the order of 1000 G (Gauss). The surface of the Sun outside the spots has a magnetic field of about a few Gauss (Bhowmik et al. 2023). Sunspots are believed to result from the interaction between the Sun’s magnetic field and turbulent convection near the surface: in regions with strong magnetic fields, convection is significantly suppressed, leading to inefficient heat transfer and consequently the formation of locally cooler and darker sunspots (Stein, 2012). They are strongly related to active solar events such as solar flares, coronal mass ejections etc. Sunspots are usually observed in groups and each group consists of different spots. A well-developed sunspot is fundamentally composed of two main parts: the umbra, situated at the center of the spot and characterized by its pronounced darkness, and the penumbra, which surrounds the umbra and appears brighter compared to the umbra.

Sunspots are generally observed in the ± 35 degrees latitude zone, called the active zone. The active events we observe on the Sun increase and decrease approximately every 11 years called the solar cycle. At the start of a solar cycle, very few sunspots, mostly small in size (Mandal et al., 2017), appear on the solar disc. Especially at the beginning of the solar cycle, sunspots observed in the latitude belt of 40-45 degrees move towards lower latitudes as the cycle progresses. Although the duration of the solar cycle is not constant, sunspots continuously form and dissipate over time. These dynamic patterns are accompanied by significant changes in sunspot properties, including umbral intensity and size, which have been linked to different phases of the solar cycle. Albregtsen and Maltby, (1978, 1981) reported the sunspot intensity varies approximately linearly with the phase of the solar cycle. Albregtsen, Joras, and Maltby (1984) analyzed the solar cycle variation of umbral intensities. Their study is based on broadband pinhole photometer intensity observations of 22 large sunspots, covering approximately 600 days during 15.5 years. They observed that the umbra/photosphere intensity ratio to be a linear function of the phase of the solar cycle. Norton and Gilman (2004) used brightness ratios and magnetic field data from the Advanced Stokes Polarimeter and the Michelson Doppler Imager (MDI) for 10 sunspot umbrae of various sizes observed between May 1998 and June 2003. They reported that the mean umbral intensity decreased in the northern hemisphere through the solar cycle. Such findings not only enhance our understanding of solar activity mechanisms but also provide observational evidence supporting the dynamo theory, which explains the Sun's magnetic field generation.

Magnetic fields can cause significant changes in the dynamics in and around the spot. The region where the magnetic field is most concentrated is the umbra of sunspots. Watanabe (2014), used Hinode data to analyze umbral dots (UDs), which are fine structures observed in the umbra. As noted by Watanabe (2014), statistical correlations offer a useful perspective on the evolution of internal sunspot structures. The author pointed out that the umbral magnetic field is not uniform during sunspot development, since the umbra forms through the aggregation of pores with varying magnetic field strengths. The strength of the magnetic field varies depending on the size and shape of the spot. Pevtsov et al. 2014 used observations made at the Mount Wilson Observatory (MWO) between May 1920 and December 1958 to investigate the properties of sunspot magnetic fields. They stated magnetic field strength increases as the sunspot area increases. A sunspot umbra typically has a vertical magnetic field, while toward the penumbra, the field lines become inclined and become largely horizontal in this region (Rempel et al., 2009; Borrero & Ichimoto, 2011). Yurchyshyn et al. (2020) used data obtained with the Visible Imaging Spectrometer on the Goode Solar Telescope (GST) to detect the origin of umbral flashes (UFs) and umbral waves (UWs). In their study, it is reported that the dark umbra center has a strong magnetic field strength on the sunspot-center side of the enhanced magnetic fields. They showed that the magnetic field in the sunspot umbra is more dynamic, and its relationship with the Sun's magnetic activity cannot be ignored. Therefore, understanding the magnetic activity of sunspots is crucial for predicting solar activity, space weather conditions, and their effects on Earth. This highlights the need for a deeper understanding of sunspot properties.

In the present study, we analyzed 16 sunspot umbrae observed in 13 different ARs with the GST broadband imager between 2015 and 2022. We obtained variations of umbral magnetic field strength with umbral area, brightness, and sunspot number. We performed regression and Pearson correlation analyses to investigate the relationships between mean umbral field strength and other parameters. The outline of the article is as follows: In Section 3, we present the data and methods used. In Section 4, we present the analysis results. In Section 5, our conclusions are presented.

2. Data and Method

2.1.Data

In this study 13 sunspot data were selected from Big Bear Solar Observatory (BBSO)/Goode Solar Telescope (GST) archive data (Figure 1). The used data set covers the 2015 – 2022 time interval (Table 1). For the analysis the Titanium Oxide (TiO) filter (7057 Å) images of each sunspot were selected. The TiO spectral band is highly sensitive to temperature, making it well-suited for observations of dark and cool regions, even inside the umbra. The resolution of TiO data per pixel is 0.034”. Also, the GST allows simultaneous TiO and Near-Infrared Imaging Spectropolarimeter (NIRIS) measurements to be taken. We used simultaneously one TiO and one NIRIS image for the analysis. The TiO filter was used to determine the umbral area and brightness, and the NIRIS filter was used to obtain the magnetic field strength. The resolution of NIRIS data per pixel is 0.083”.

Table 1. *List of the analyzed sunspots*

Number	NOAA Active Region Number	Observation Time	Sunspot Location	TIO Time (UT)	NIRIS Time (UT)	Daily Sunspot Number
1	AR12384	14/07/2015	S18W19	17:52:02	17:52:09	43
2	AR12411	08/09/2015	N14E13	16:30:38	16:30:45	42
3	AR12565 **(dual umbra)**	14/07/2016	N04E30	16:41:25	16:41:24	58
4	AR12717	01/08/2018	S07E15	16:48:46	16:48:48	12
5	AR12720	25/08/2018	N08W38	17:04:47	17:04:48	32
6	AR12767	28/07/2020	S20W18	16:23:56	16:24:00	20
7	AR12770 **(dual umbra)**	08/08/2020	N23E11	17:18:02	17:18:09	12
8	AR12776	20/10/2020	S13W17	18:01:06	18:01:03	14
9	AR12902	30/11/2021	N18W03	16:35:57	16:35:52	59
10	AR12934	24/01/2022	S25E16	17:43:37	17:43:33	33
11	AR13046	06/07/2022	N18W05	18:32:03	18:32:10	82
12	AR13053	12/07/2022	N16W20	20:02:43	20:02:50	114
13	AR13147 **(dual umbra)**	20/11//2022	S12E20	17:50:28	17:50:26	84

The umbra and penumbra were separated by applying a binary filter based on intensity threshold (Calisir et al, 2023). The threshold value selected as 0.65 for developed penumbra, while it has been used to be 0.70 for sunspots with undeveloped or poorly developed penumbra (see Figure 2). The threshold value was determined as a multiple of the mean intensity of the entire sunspot, including the quiet sun area around the sunspot.

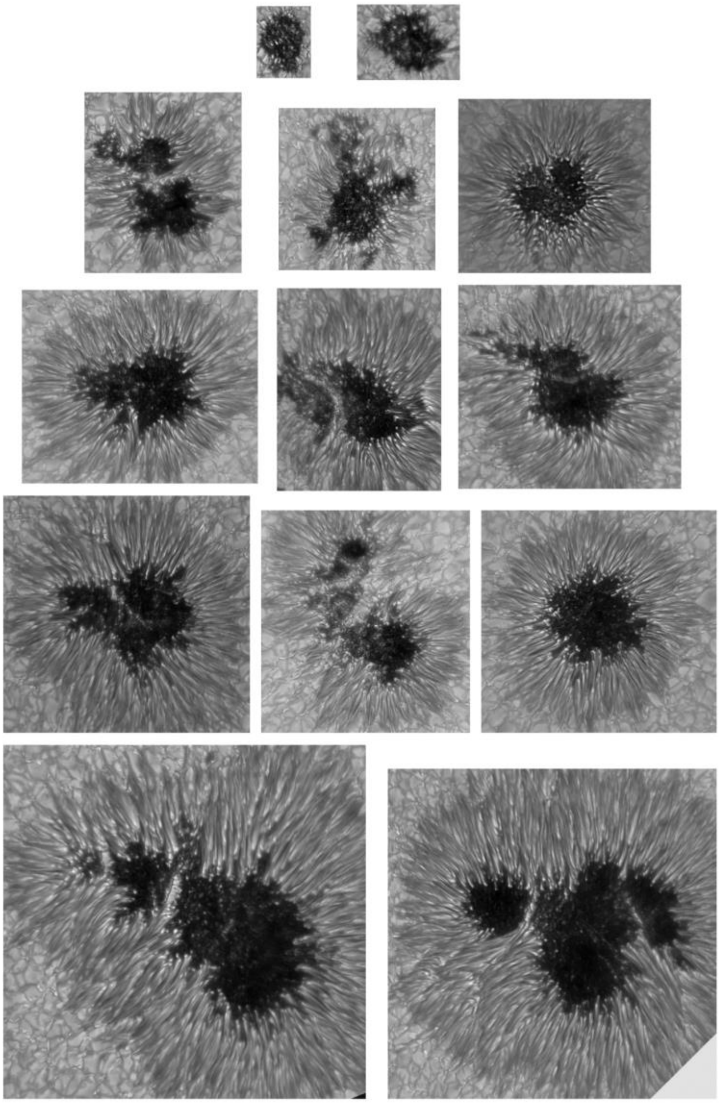

Figure 1. *Images of all sunspots used in the study.*

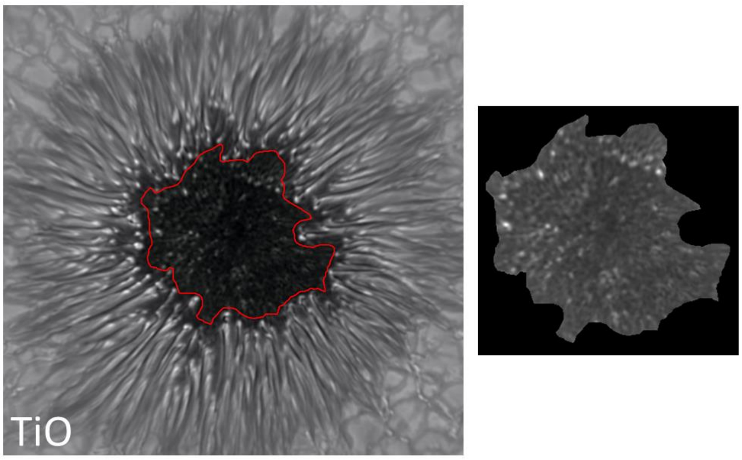

Figure 2. *Left panel: TiO image (AR 12384). Red contour: Detection of the umbra. Right Panel: The zoomed in extracted umbral core.*

2.2.Calculation of Umbral Parameters

Umbral Area: To calculate the umbral area, the umbra was separated from the penumbra, and the area of the remaining image was calculated in terms of the total number of pixels and it was converted to Mm^2.

Umbral Brightness: The mean pixel value within the umbral area was calculated for each image.

Umbral Magnetic Field: For the umbral magnetic field we selected the exactly the same region from the TiO data (Figure 3). To calculate the intensity (strength) of the umbral magnetic field; similarly, the pixel values within the field were averaged.

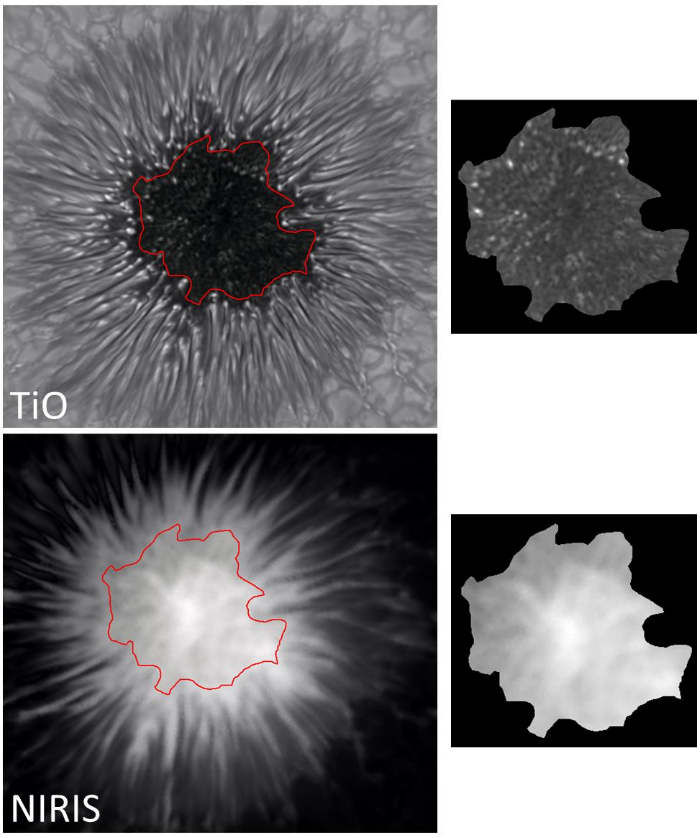

Figure 3. *Left panel: TiO and NIRIS images (AR 12384). Right Panel: The zoomed in extracted umbral cores.*

2.3.Sunspot Number (SSN)

To investigate the solar cycle dependency of the obtained mean umbral magnetic field strength, we compared it with the daily sunspot number data available at SIDC (https://www.sidc.be/silso/datafiles). We added the daily sunspot numbers for the corresponding dates. (It is shown as a yellow column in Table 1.)

3. Results

We used almost simultaneously 13 images from NIRIS and TiO filters. Since some sunspots contain double umbra (AR 12565, AR 12770 and AR 13147), a total of 16 umbra were analyzed. We obtained the mean umbral magnetic field strength, umbral area, and umbral brightness for each sunspot (Table 2).

Table 2. *Mean physical parameters of analyzed sunspots.*

Umbra	Mean Umbral Magnetic Field (Gauss)	Mean Umbral Area (Mm2)	Mean Umbral Brightness (Relative Intensity)
20150714	1494.2	47.54	0.37
20150908	1531.72	28.06	0.43
20160714 **Large Umbra**	1892.09	136.48	0.33
20160714 **Small Umbra**	1532.2	25.09	0.28
20180801	1367.21	12.99	0.56
20180825	1655.65	25.33	0.50
20200728	1974.78	44.71	0.32
20200808 **Large Umbra**	1849.61	19.80	0.34
20200808 **Small Umbra**	989.99	11.69	0.42
20201020	1938.02	44.90	0.35
20211130	1748.68	25.10	0.50
20220124	1954.99	54.98	0.35
20220706	1746.24	19.91	0.43
20220712	1177.14	24.71	0.35
20221120 **Large Umbra**	2098.64	121.80	0.30
20221120 **Small Umbra**	1766.36	18.77	0.33

Relationship between umbral magnetic field and umbral area, brightness, sunspot number

We performed regression and Pearson correlation analyses to investigate the relationships between mean umbral field strength and other parameters (mean umbral area, mean umbral brightness and sunspot number) (Figure 4). Their error of correlations coefficients were calculated by using the standard error calculation method. The results are presented in Table 3.

Table 3. *Summary of the obtained correlation coefficients (r).*

	Mean Umbral Area (Mm^2)	Mean Umbral Brightness (Intensity)	Sunspot Number
Mean Umbral Magnetic Field Intensity (Gauss)	**+0.64 ± 0.21**	**-0.39 ± 0.25**	**0.33 ± 0.26**

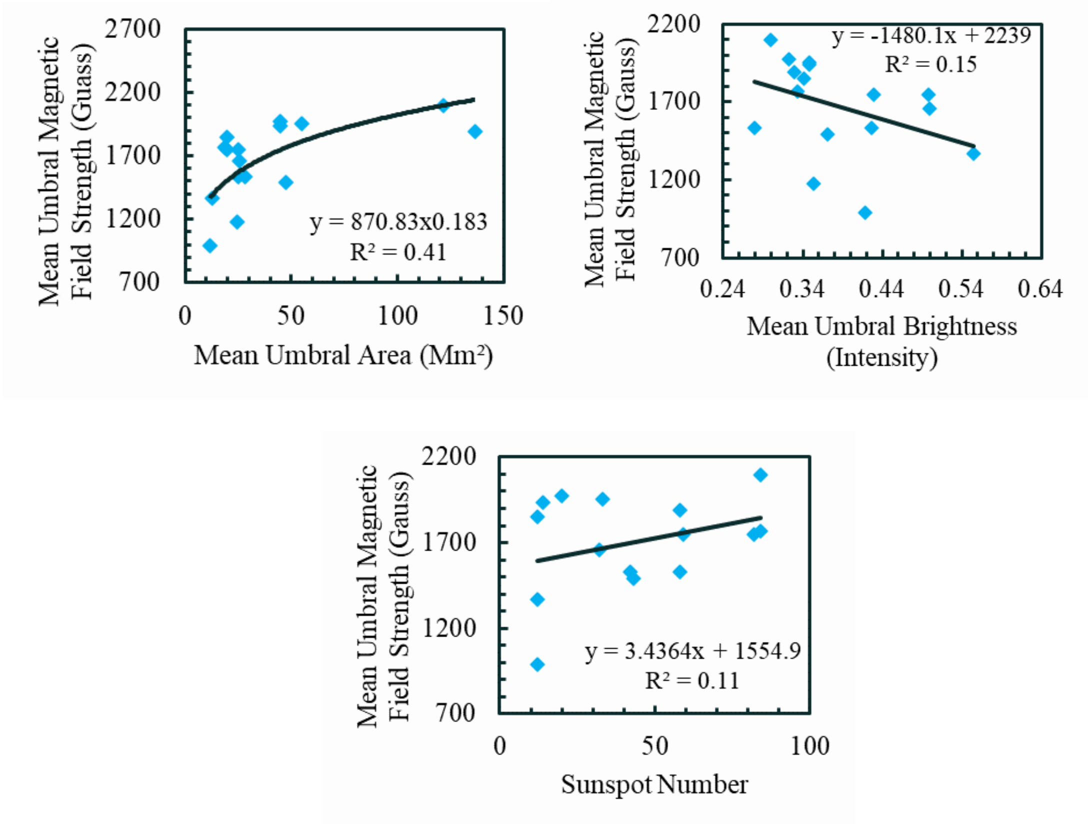

Figure 4. *Relationships between umbral magnetic field and umbral area, brightness, sunspot number in the analyzed on all 16 sunspot umbra.*

Pearson correlation analyses were carried out to reveal the relationship between umbral magnetic field intensity and above parameters (sunspot area, brightness and sunspot number). An examination of Table 3 and Figure 4 clearly shows that there are significant and systematic relationships between umbral magnetic field strength and these parameters. According to the analysis results, a positive correlation was found between umbral magnetic field strength and both umbral area and sunspot number. In contrast, as umbral brightness increases, the magnetic field strength decreases, indicating an inverse relationship. This suggests that brighter umbrae are generally associated with weaker magnetic fields. A comparison of the correlation coefficients revealed that the strongest correlation with umbral magnetic field strength was found with umbral area, while the weakest correlation was with sunspot number. All correlation coefficients were found to be statistically significant, and these results strongly support the idea that magnetic field strength in sunspot umbrae is related to observed local structures and overall solar activity.

4. Conclusions and Discussions

We analyzed 16 sunspot umbrae observed in 13 different ARs with the GST broadband imager. We obtained variations of umbral magnetic field strength with umbral area, brightness, and sunspot number. Our main results are as follows:

- The mean umbral magnetic field strength increases exponentially as the mean umbral area increases.

- The mean umbral magnetic field strength decreases linearly with the mean umbral brightness. On the contrary, it increases linearly with the sunspot number.

- We found that all obtained correlation coefficients are meaningful.

The magnetic field strength varies with the size of the sunspot; it is higher in larger spots, while it is lower in spots with smaller umbrae. This result confirms the findings of Pevtsov et al. (2014) and clearly emphasizes that the relationship between sunspot size and magnetic field strength should not be overlooked. Watanabe (2014) stated that the umbral magnetic field is not homogeneous during the evolution of sunspots and that the umbra is formed by the merging of dynamics with varying magnetic field strengths. Yurchyshyn et al. (2020) reported that the dark umbra at the center of the sunspot has a strong magnetic field. In this study, we found that the magnetic field strength decreases linearly as the umbral brightness increases. Observations have also shown that the darker region in the center of the umbra has strong magnetic fields. This finding shows that the homogeneity of the umbra is related to the magnetic field. The change in spot dynamics with increasing magnetic field strength and the corresponding decrease in spot brightness indicate that there are significant differences in the energy transport and observed structures inside the umbra.

Previous studies reported that umbral brightness is linked to different phases of the solar cycle and are associated with significant changes in sunspot characteristics (Albregtsen and Maltby, 1978, 1981; Albregtsen, Joras, and Maltby, 1984; Norton and Gilman, 2004). Albregtsen, Joras, and Maltby (1984), have confirmed the earlier finding (Albregtsen and Maltby, 1978, 1981) the sunspot intensity varies linearly with the phase of the solar cycle. They reported the high correlation between the intensities of the umbra and the penumbra of the same spot suggests that the mechanism which is responsible for the solar cycle intensity variations acts on the whole sunspot, and not only locally on the umbra. Norton and Gilman (2004), found that the mean umbral intensity in the northern hemisphere decreased during the solar cycle, reaching a minimum around the time of sunspot maximum. They reported this may be possible evidence of the toroidal field strength peaking at solar maximum. Such findings not only improve our understanding of solar activity mechanisms but also provide observational evidence supporting the dynamo theory that explains the formation of the Sun's magnetic field. On the other hand, the linear relationship observed between umbral magnetic field strength and sunspot number indicates that even the magnetic properties of a single sunspot are not independent of the Sun's large-scale magnetic activity, but rather are related to the solar cycle. This suggests that the magnetic field structures of umbrae are driven not only by local morphological conditions, but also by the global magnetic dynamics of the Sun. Taken together, these findings emphasize that the magnetic field structures of sunspots are shaped in a complex manner and that these structures can be linked to the solar cycle.

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