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Sunspot magnetic fields in solar cycle 24 on measurements at Crimea and Mount Wilson

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ABSTRACT

We present a comparative analysis of 6235 measurements of maximum magnetic fields of the same sunspots obtained at the Crimean Astrophysical Observatory (CrAO) and the Mount Wilson Observatory (MWO) from 2009 to 2019, with the intensity B exceeding 1.5 kGs on CrAO data. It has been established that the average values of the magnetic fields derived at CrAO and MWO are 2053 and 1914 Gs, respectively. The correlation coefficient between the magnetic field measurements at different observatories is 0.63 ± 0.01, and it decreases with increasing B. The difference between the average values of magnetic fields exceeds 500 Gs for sunspots with $B \geq 2.5$ kGs. The maximum values of sunspot magnetic fields for the period under consideration according to CrAO and MWO data are 4.6 and 2.7 kGs, respectively. Possible reasons for data discrepancies are discussed.

Key words: Sun, solar cycle, sunspot magnetic field measurements

1 Introduction

The magnetic field of the Sun, which determines its activity, is concentrated in the sunspot umbrae. It is not surprising that many space- and ground-based observatories are currently monitoring the magnetic field strength of sunspots. Despite significant technical achievements in this important area of heliophysics, the simplest and accordingly most reliable time-tested methods based on the analysis of simple Zeeman triplets do not lose their relevance. In this case, the distances between sigma components proportional to the magnetic field strength are measured using a circular polarization analyzer. Such measurements have been carried out at the Mount Wilson Observatory (MWO) from 1917 to the present day. However, for various reasons, the MWO time series cannot be considered continuous up to 2007 (Livingston et al., 2006; Hale et al., 1919; Pevtsov et al., 2019). In turn, measurements of sunspot magnetic fields have been carried out with the Solar Tower Telescope 2 (STT-2) of the Crimean Astrophysical Observatory (CrAO) since 1957 (Stepanov, Petrova, 1958).

Previously, a comparison of measurements of the maximum magnetic fields B of the same sunspots has already been carried out according to the data from CrAO and MWO, taking into account the time shift from 8 to 15 hours (Tsap et al., 2019). However, the authors limited themselves to the analysis of sunspots with the strength $B \geq 2.5$ kGs (according to CrAO data) for the period from 31.07.2010 to 01.10.2017. The Pearson correlation coefficient for these measurement data at CrAO and MWO turned out to be 0.22, which is most likely due to the shortcomings in the calibration of measurements of strong fields at MWO (Tsap et al., 2019). In addition, a possible reason for such a low correlation coefficient could be related to the shortcomings of the data processing technique in Tsap et al. (2019). In particular, in the CrAO data array, all measurements of a given sunspot were taken into account for the observation period, while according to MWO data, only one corresponding value was considered. Lozitska et al. (2015) also performed a detailed comparison of the results of measurements of sunspot magnetic fields at CrAO and MWO for the period from 2010 to 2012. However, the samples were compared as a whole, without specifying the corresponding objects of measurement. In addition, the polarity of sunspots was taken into account, which implies the division of a sample of measurements into two groups.

In the previous work of Akhtemov et al. (2023), we have already conducted an analysis of the evolution of the quarterly average maximum magnetic field strengths of the same groups of sunspots with $B \geq 1500$ Gs obtained at MWO and with CrAO STT-2 for the period from 2015 to 2019. However, the authors limited themselves to comparing the magnetic fields for a very limited sample in the region of minimum of solar cycle 25. The correlation between the groups of sunspots in given ranges of magnetic field strength was also not considered. Therefore, the aim of the presented work is to conduct a comparative analysis of the maximum magnetic field strengths of the same sunspots with $B \geq 1500$ Gs, ≥ 2000 Gs, and ≥ 2500 Gs obtained at MWO (B_{MWO}) and CrAO (B_{CRAO}) for the period between 2009 and 2019.

2 Observations and their processing

On Mount Wilson, where there are on average about 330 clear days per year, observations were carried out in the FeI 5250 Å line with the Lande factor $g = 3$ for the period that was explored by us with the STT (Livingston et al., 2006). Meanwhile, the magnetic field was measured in the FeI 6302 Å line with $g = 2.5$ in Crimea (Severnyi, Stepanov, 1956; Stepanov, Petrova, 1958), whereas the number of clear days per year (Nauchny settlement) is about 220. The measurement accuracy on both instruments did not exceed 100 Gs. More detailed information about the characteristics of the instruments and measurement methods used can be found in Tsap et al. (2019).

The maximum values of sunspot magnetic fields obtained with STT-2 at CrAO were processed and posted on the observatory's website in the form of sketches, one of which is shown in Fig. 1. It should be noted that the table in Fig. 1 makes it possible to find the correspondence between the numbers of active regions, assigned to each group of sunspots from the beginning of the year at the Crimean observatory, and the numbers of active regions according to the National Oceanic and Atmospheric Administration (NOAA) classification. For sunspots and pores, in addition to the values of the magnetic field, polarity was also determined. The southern and northern magnetic polarities are denoted by the letters *S* and *N*, respectively. At MWO, the data were also presented in the form of sketches of the solar disk, rotated by 180° relative to the disk configuration adopted at CrAO, with the coordinates of the groups, but without their numbers (Fig. 2). The letters *R* and *V* denote the magnetic fields of the northern and southern polarity, respectively, and the letters *N*, *S*, *E*, *W* denote the coordinates of the sunspot groups on the solar disk.

We compared the values of the magnetic fields of the same sunspots following from the spectral measurements of the splitting of the Zeeman components carried out at the Mount Wilson Observatory and with the STT-2 at CrAO from 2009 to 2019 without taking into account polarity.

Table 1. Example of comparing measurements of maximum magnetic field strengths (≥ 1500 Gs) of the same sunspots in a group obtained at CrAO and MWO.

Measurement date	MWO	CrAO
25.10.2009	17	15
	18	15
	22	15
26.10.2009	24	20
27.10.2009	24	22
	18	18
	22	22
30.10.2009	20	21
10.11.2009	15	17

An example of comparing measurements of sunspot magnetic fields at CrAO and MWO is shown in Fig. 3. Note that the time difference for the case under consideration was about nine hours.

The processed data of 6235 measurements, which correspond to each other in the best way taking into account a time shift between the observation points, were summarized in a table, a part of which is presented below (Table 1). As can be seen, a group could often have several sunspots with a

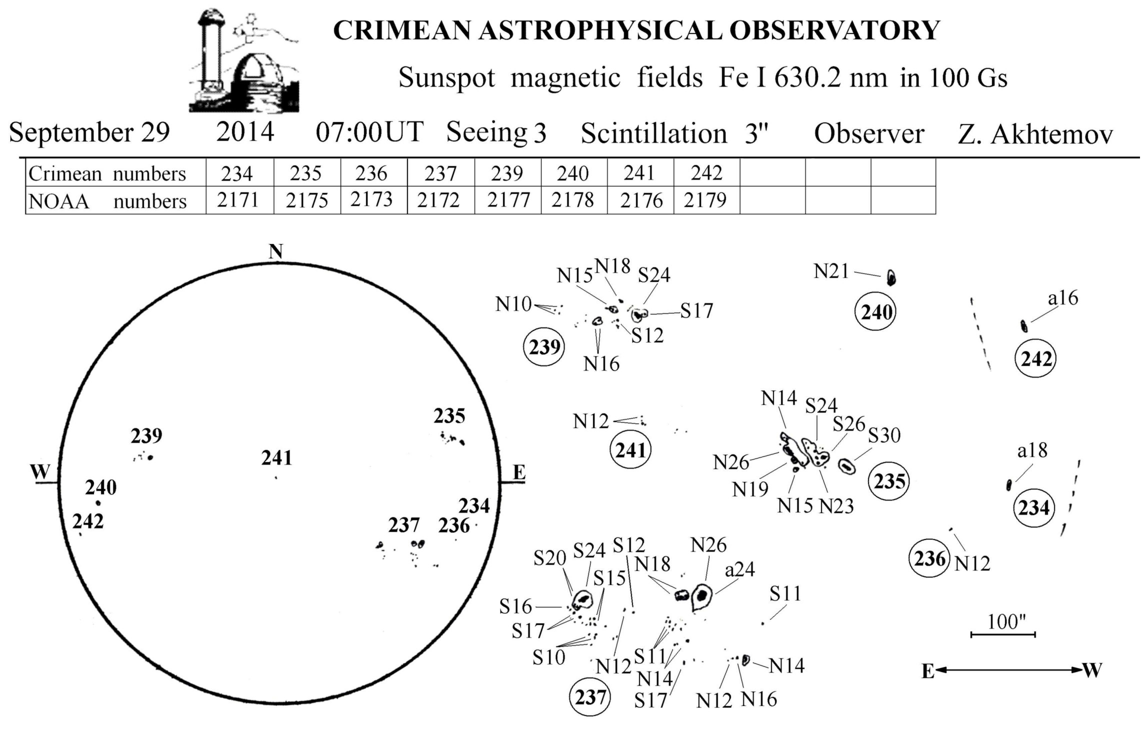

Fig. 1. Sketch of sunspots with measured magnetic fields according to observations on 29.09.2014 at CrAO.

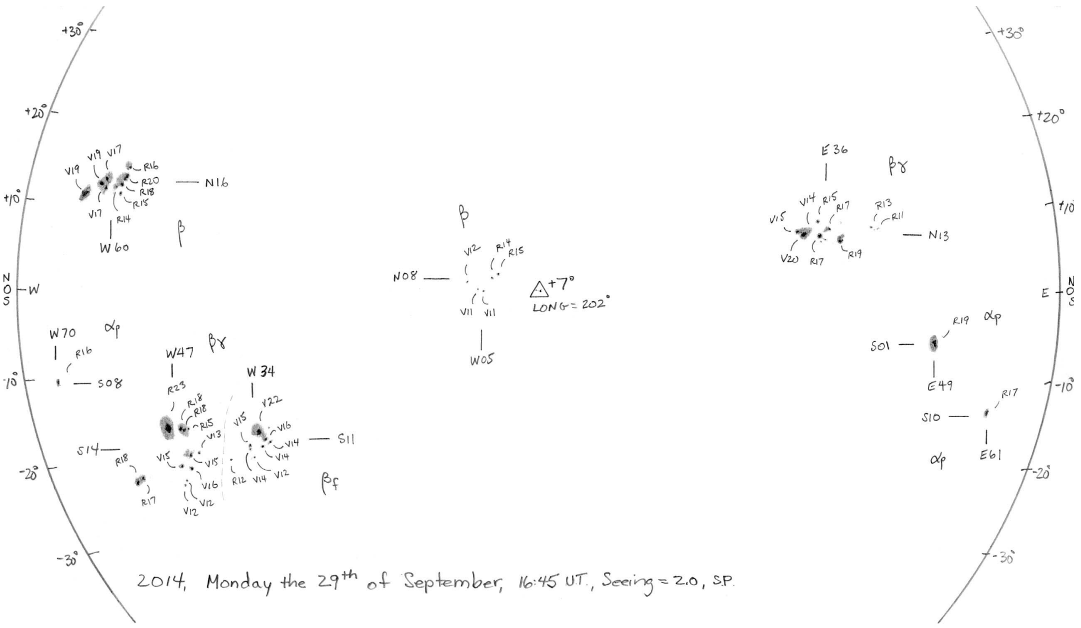

Fig. 2. Sketch of sunspots with measured magnetic fields according to observations on 29.09.2014 at MWO obtained with a delay of about nine hours relative to the measurement data from CrAO (Fig. 1).

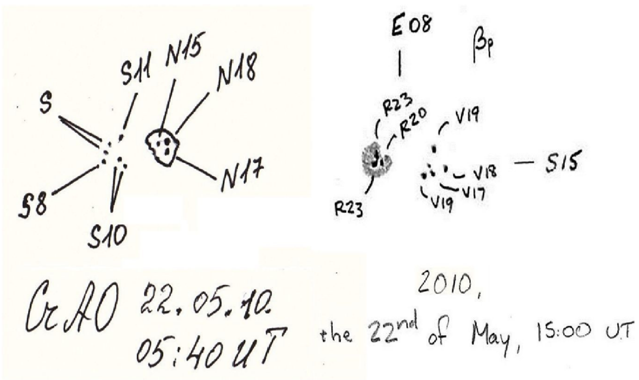

Fig. 3. Example of comparing measurements of the magnetic field of a group of sunspots according to the data from CrAO (left) and MWO (right).

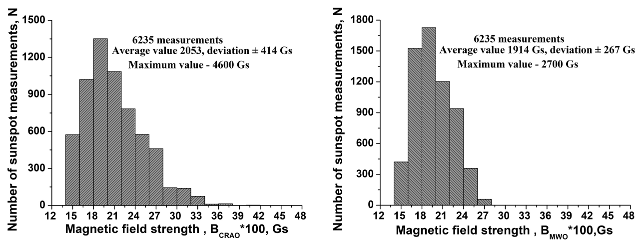

Fig. 4. Dependence of the number of sunspot measurements on the magnetic field strength obtained from CrAO (left) and MWO (right) data for the period between 2009 and 2019 for $B \geq 1500$ Gs.

strength exceeding a given value of the magnetic field. At the same time, the difference in strengths could reach 700 Gs.

2.1 Statistical analysis of measurements of sunspot magnetic fields at CrAO and MWO

Visualization of the data from the above table in the form of diagrams representing the distribution of the number of sunspot measurements (the total number of measurements is 6235) depending on the value of their magnetic field with $B \geq 1500$ Gs and an interval of 200 Gs is shown in Fig. 4. First of all, it is noteworthy that the most frequently occurring magnetic field values in both observatories fall within the range of 1600–2200 Gs. The average values of $B_{\rm av}$ from observations at CrAO and MWO are 2053 and 1914 Gs, respectively, while the maximum strengths for the entire observation period were 4600 and 2700 Gs.

If we select the values of sunspot magnetic fields with $B \geq 2000$ Gs from the general array of CrAO data and determine the corresponding measurement values from MWO, then upon visualization we will obtain the diagrams shown in Fig. 5. In this case, the total number of measurements decreased by almost half and amounted to 3281. However, according to CrAO data, magnetic fields with $B = 2000$–2600 Gs and $B_{\rm av} = 2360$ Gs are most common. Meanwhile, according to MWO, the peak in the number of measurements falls within the range of 1800–2400 Gs and $B_{\rm av} = 2039$ Gs. The increase in the difference between the average values of $B_{\rm av}$, which now amounts to 321 Gs, is noteworthy.

Finally, taking the CrAO data array with $B \geq 2500$ Gs and comparing the corresponding measurements from MWO, we obtain histograms of the distribution for only 1064 measurements of sunspot magnetic field strength (Fig. 6). According to CrAO data, the maximum number of measurements falls in the range of 2500–2800 Gs and $B_{\rm av} = 2747$ Gs,

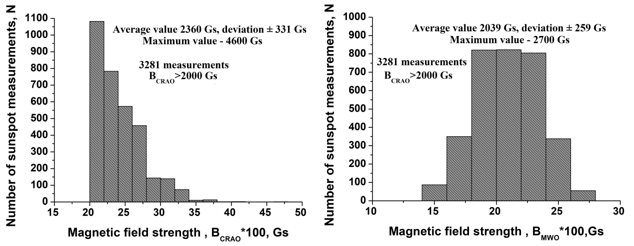

Fig. 5. Dependence of the number of sunspot measurements on the magnetic field strength obtained from CrAO (left) and MWO (right) data for the period between 2009 and 2019 for $B \geq 2000$ Gs.

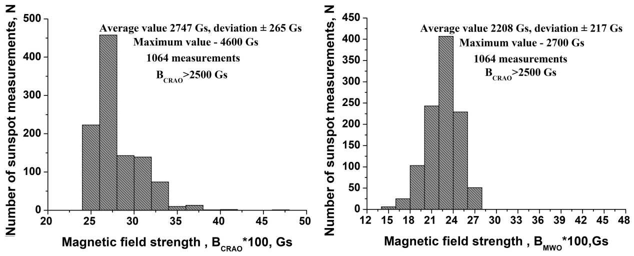

Fig. 6. Dependence of the number of sunspot measurements on the magnetic field strength obtained from CrAO (left) and MWO (right) data for the period between 2009 and 2019 for $B \geq 2500$ Gs.

while according to MWO data, we have 2000–2600 Gs and B_{av} = 2208 Gs, respectively. Thus, the difference of B_{av} significantly increases and reaches a value exceeding 500 Gs.

The scatter plot between the values of sunspot magnetic fields with $B \geq 1500$ Gs obtained at CrAO and MWO is presented in Fig. 7. As can be seen from numerical calculations, for the studied observation period from 2009 to 2019, the Pearson correlation coefficient turned out to be 0.63 ± 0.01, which indicates a satisfactory agreement between the measurements at CrAO and MWO. However, a more detailed analysis showed that the correlation coefficients between the values of sunspot magnetic fields obtained at MWO and CrAO for $B \geq 2000$ and ≥ 2500 Gs are equal to 0.52 ± 0.01 and 0.35 ± 0.03, respectively.

3 Discussion of results and conclusions

The spectral method for measuring magnetic fields still remains the simplest and most reliable. This is explained by the fact that the results are not affected by the atmosphere model, the effect of signal saturation, weak intensity of radiation in a source, instrumental polarization, etc. Despite the time difference between measurements of at least eight hours, the values of the magnetic fields of the corresponding sunspots with $B \geq 1500$ Gs obtained at CrAO and MWO for the period from 2009 to 2019 are in good agreement. Meanwhile, for the sunspots with $B \geq 2500$ Gs, the correlation coefficient noticeably decreases and amounts to only 0.35 ± 0.03. The histograms in Figs. 5 and 6, which turned out different, suggest that the measurements of magnetic fields with

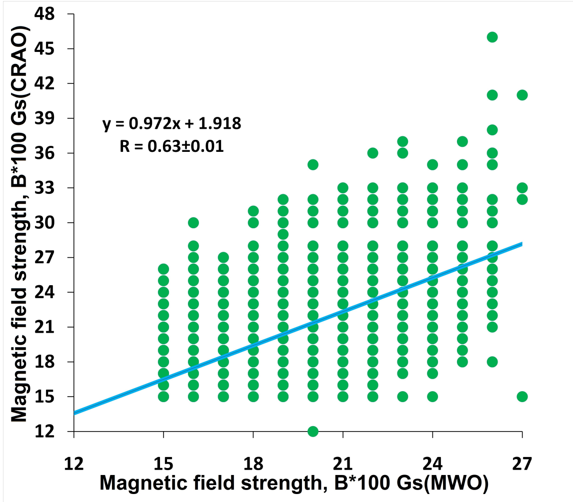

Fig. 7. Scatter plot of magnetic field measurements at CrAO (vertical axis) and MWO (horizontal axis).

$B \geq 2000$ Gs at CrAO and MWO differ significantly. In particular, this is indicated by the highest values of the obtained strengths at CrAO (4.6 kGs) and MWO (2.7 kGs), as well as the correlation coefficients for different intervals of B. In our opinion, the discovered discrepancy is most likely caused by not entirely correct calibration (Tsap et al., 2019), edge effects associated with the angle between the direction of the magnetic field and the line of sight, subjectivity of observers, and by design features of the equipment used. An important role can also be played by scattered light caused by the Earth's atmosphere, image jitter, inaccurate placement of the sunspot center on the spectrograph slit (Severnyi, Stepanov, 1956), which requires additional research.

Let us briefly formulate the main results of the work:

1. For the data of 6235 measurements of the magnetic fields of the same sunspots with $B \geq 1500$ Gs at CrAO and MWO, the Pearson correlation coefficient is 0.63 ± 0.01.
2. In both observatories, the maximum number of sunspot measurements falls within the range of 1600–2200 Gs.
3. Measurements at MWO on average give underestimated values of sunspot magnetic fields compared to CrAO data; the difference in B_{av} values noticeably increases with increasing B and for sunspots with $B \geq 2500$ Gs reaches a value exceeding 500 Gs.
4. The maximum values of sunspot magnetic fields for the period under consideration according to CrAO and MWO data are 4600 and 2700 Gs, respectively.
5. According to CrAO and MWO data, the Pearson correlation coefficients for sunspots with $B \geq 2000$ and 2500 Gs are equal to 0.52 ± 0.01 and 0.35 ± 0.03, respectively.
6. The average values of sunspot magnetic fields B_{av} with $B \geq 1500$, 2000, and 2500 Gs for CrAO were 2053, 2360, and 2747 Gs, respectively, while for MWO, B_{av} = 1914, 2039, and 2208 Gs.

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