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LONG-TERM TRENDS IN SUNSPOT MAGNETIC FIELDS

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ABSTRACT

Recent studies indicate that a maximum field strength in sunspots shows a gradual decrease over the last several years. By extrapolating this trend, Penn & Livingston proposed that sunspots may completely disappear in the not-so-distant future. To verify these recent findings, we employ historic synoptic data sets from seven observatories in the former USSR covering the period from 1957 to 2011 (from 1998 to 2011, observations were taken at only one observatory). Our results indicate that while sunspot field strengths rise and wane with solar cycle, there is not a long-term trend that would suggest a gradual decrease in sunspot magnetic fields over the four and a half solar cycles covered by these observations.

Key words: Sun: activity– sunspots – Sun: surface magnetism

1. INTRODUCTION

Although solar activity can be represented by various solar features, sunspots are a hallmark of the solar cycle. Magnetic properties of sunspots are ultimately tied to the solar dynamo. The last prolonged deep minimum of solar activity that set records in the number of spotless days raised a possibility of potentially dramatic changes in near future solar cycles (Hill et al. 2011). Recent papers by Penn & Livingston (2006, 2010) had suggested that a maximum field strength in sunspots may have gradually decreased over the last several years. By extrapolating this trend, they proposed that sunspots (as we know them) may completely disappear in the not-so-distant future. On the other hand, Watson et al. (2011) investigated magnetic flux changes over the Cycle 23 and found only a minor decrease in strong magnetic flux of the active regions. There are differences in the measurements between these two studies. Penn & Livingston (2006) measured true field strength represented by the separation of two Zeeman components of the magnetically sensitive spectral line Fe I 1564.8 nm. Watson et al. (2011) employed longitudinal flux measurements from the Michelson Doppler Imager (MDI; Scherrer et al. 1995) on board the *Solar and Heliospheric Observatory* spacecraft. They computed the field strength under the assumption that the magnetic field is vertical in sunspot umbrae. While, in general, this is a reasonable assumption, there are studies indicating a non-vertical orientation of magnetic fields in sunspot umbrae (e.g., fields in leading and following sunspots could be inclined toward each other; see Karachik et al. 2010). MDI line-of-sight magnetograms will saturate in strong magnetic fields (for a description of magnetic saturation see Hagyard & Pevtsov 1999). There is also a known nonlinearity in MDI response to weak and strong fields (Berger & Lites 2003).

In this Letter, we investigate changes in the field strength of sunspot magnetic fields in Solar Cycles 19–22 using historic synoptic observations from seven observatories in the former USSR.

2. DATA SETS

The synoptic solar program in the USSR was established in the early 1950s. By mid-1950s, regular measurements of the magnetic field strength were started at both the Pulkovo and Crimean observatories. Later, a network of solar observing stations was created to mitigate the effects of the day–night cycle on the observations and to ensure a more complete daily coverage. In the present study, we employ daily observations of sunspot magnetic fields from seven observatories (see Table 1 for details). Summaries of these observations were published in the monthly Bulletin of Solnechnye Dannye (Bulletin of Solar Data in Russian), which can be accessed at http://www.gao.spb.ru/english/database/sd/daily_sun_charts.htm.

To measure the magnetic field strength, a multi-strip compound quarter-wave plate (backed by a polarizer) was placed in front of a spectrograph slit. For a graphical representation of a similar optical setup, the reader is referred to Figure 5.7 in Bray & Loughhead (1964). Separation between the two Zeeman components of a magnetic-field-sensitive spectral line either was measured manually by the observer or the spectra were photographed for later measurements. As a rule, the observations were taken at Fe I 630.2 nm, although other lines were used as well. With the exception of the Pulkovo and Crimean observatories, the data were taken with near identical instrumentation, which includes a horizontal ATsU-5 coelostat-type telescope (diameter of image in prime focus is about 18 cm) and an auto-collimated ASP-20 spectrograph (with a spectral grading of 600 lines mm^{-1}). Pulkovo observatory used a horizontal coelostat-type telescope with a larger aperture and focal length (diameter of the solar image in prime focus is about 50 cm). At the Crimean observatory, the data were initially taken at the Tower Solar Telescope BST-1 (the diameter of the solar image in prime focus is about 70 cm). In 1966, the observations were moved to a horizontal solar telescope (probably ATsU-5), and in early 1970s to a new Tower Solar Telescope, BST-2 (Tsap 2008). These later observations had a solar image size in prime focus of about 30 cm in diameter. Measurements at all observatories were rounded to a nearest 100 G (e.g., 1900 G, 2000 G, 2100 G, etc.).

In 1998, as part of a preservation project supported by the Russian Foundation for Basic Research, data from all seven observatories were digitized and made available online as the "Combined Database of Sunspot Magnetic Fields" at http://www.gao.spb.ru/database/mfbase/gindex.html.

Table 1
Summary of Observations

Station	Period of Observations	Station Name
1	1957–1961, 1963–1997	Main (Pulkovo) Astrophysical Observatory
2	1957–1961, 1963–1974, 1976, 1978, 1981–1995, 1998–2011	Crimean Astrophysical Observatory
3	1966–1973, 1976–1979	Shamakhy Astrophysical Observatory
4	1967–1974, 1976–1979	Astronomical Observatory of Ural State University
5	1964–1967, 1970–1971, 1985–1995	Sayan Solar Observatory of Institute of Solar-Terrestrial Physics
6	1957–1961, 1964–1966	Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN)
7	1966–1973, 1976–1989	Ussuriysk Astrophysical Observatory

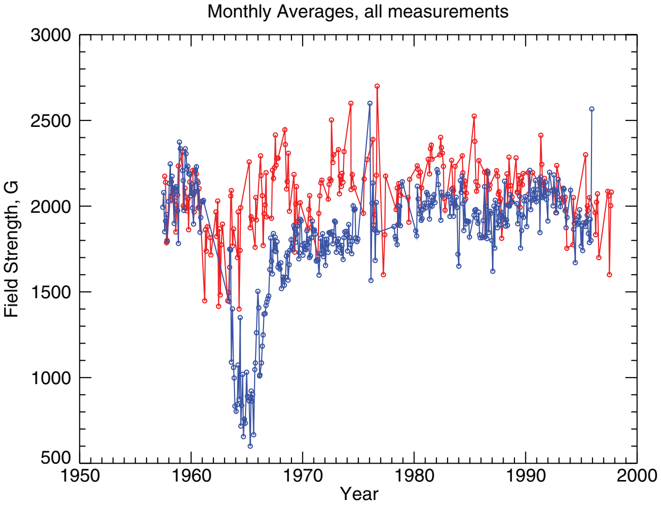

Figure 1. Monthly averages of sunspot field strengths as measured at Pulkovo (red) and Crimean (blue) observatories. Only the data from the original synoptic program database are shown. Newer observations from the Crimean observatory (from 1998 to 2011) are only included in Figures 3 and 4.

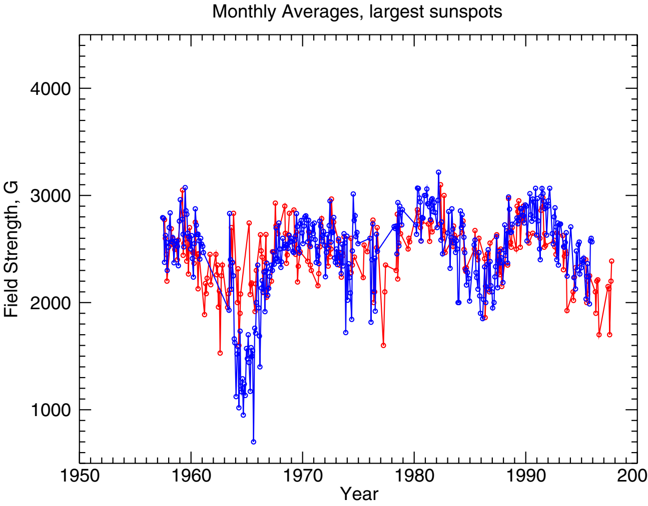

Figure 2. Monthly averages of the daily maximum field strength in sunspots from Pulkovo (red) and Crimean (blue) observations.

In 1998, the Crimean observatory had re-started the observations of sunspot field strengths. These new data are added to the above data set.

3. ESTABLISHING A RELATIONSHIP BETWEEN THE DATA SETS

Figure 1 shows the monthly averaged field strengths for Pulkovo (red color) and Crimea (blue color)—two observatories with the most complete coverage in observations. It is clear that the raw data are not well correlated. Monthly averages from the Pulkovo observatory show some variations, but there is not a long-term trend over the 40 years of these observations. In contrast, the field strengths measured at the Crimean observatory exhibit a significant decline during the period of 1964–1966 and a gradual increase from 1967 to 1985. Unusually low field strengths observed in 1964–1965 coincide with changes in instrumentation at the Crimean observatory in 1966 and early 1970s (see Section 2). On the other hand, comparing selected daily drawings from both observatories we find that the field strengths measured in major sunspots are not significantly different. Further examination of daily drawings indicates a noticeably larger number of small features (small pores and multiple umbrae inside sunspots) for measurements taken at the Crimean observatory in 1964–1965, whereas the drawings from Pulkovo from that period are less rich on such small-scale magnetic features. The above differences may then be caused by a difference in image scale in the prime focus and atmospheric seeing conditions at the two sites. The addition of a significant number of features with weaker field strengths inevitably lowers the average field strength.

However, one would expect that the image scale and the atmospheric seeing may have a lesser effect on the detectability of the larger sunspots. Indeed, if we select only the largest field strength measured on the solar disk each day, the data show much better correlation (Figure 2). The Crimean data still show a dip around 1963–1965 in field strengths, albeit with a reduced amplitude. With the exception of this dip, the monthly averaged largest sunspot field strengths show a good correlation between Crimean and Pulkovo data sets. The Spearman rank correlation coefficient is $r_S = 0.64$ with the probability of no correlation at 10^{-21}. The Kolmogorov–Smirnov (K-S) test (e.g., Press et al. 1992) applied to the Crimean and Pulkovo data sets (excluding the 1964–1965 data) indicates that statistically the two sets are drawn from the same parent distribution at a 95% confidence level. The same approach of selecting sunspots with the strongest field strength for each day of observations was applied to data from all seven observatories. In all cases, we see a significant improvement in the correlation between the data sets.

As the next step, we combined the individual data to a single set by re-scaling the field strengths (B) from the six observatories to the Pulkovo data as follows:

$$B_{i\to 1} = (B_i - \overline{B_i})\frac{\sigma_1}{\sigma_i} + \overline{B_1}, \tag{1}$$

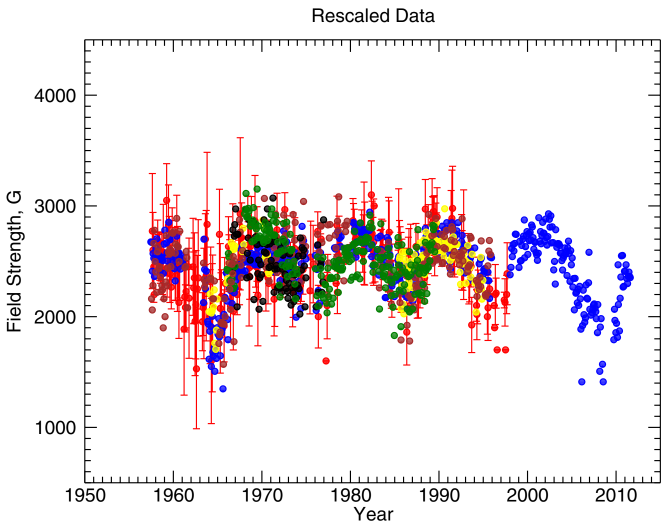

Figure 3. Monthly averages of daily strongest sunspot field strengths for all seven observatories re-scaled to the Pulkovo data set. Data are color coded as follows: station 1—red; station 2—blue; station 3—black; station 4—brown; station 5—yellow; station 6—turquoise; station 7—green. For comparison, the Pulkovo data are shown with error bars. The amplitude of the error bars is similar for all stations. Newer observations from the Crimean observatory (from 1998 to 2011) were re-scaled to the Pulkovo data similar to the Crimean data from 1957 to 1995 period.

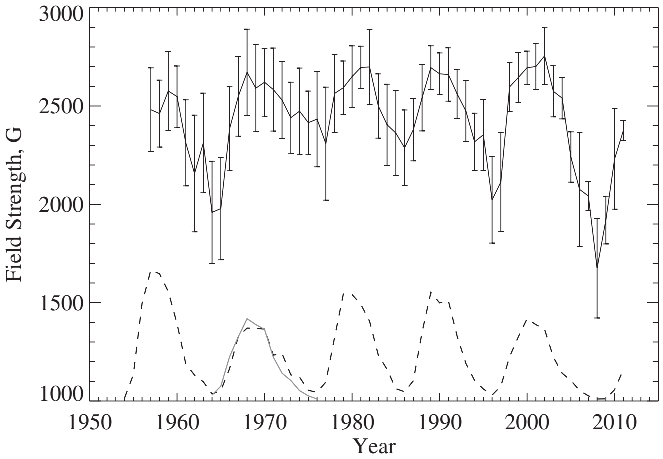

Figure 4. Yearly averages of the combined data set shown in Figure 3. Error bars correspond to ±σ, standard deviations of mean value. For comparison, the dashed line in the lower part of figure shows the annual international sunspot numbers (not in scale). The solid gray line overplotted on Cycle 20 corresponds to sunspot numbers for Cycle 23 (shifted to match beginning of Cycle 20).

where the subscript i (=2,7) designates the station number from Table 1 (subscript "1" marks the Pulkovo data), $\overline{B}$ corresponds to the mean of the distribution of field strengths for station i, and σ is its width (standard deviation). This scaling does not affect the correlation between the individual subsets, but it normalizes their statistical properties. The parameters for scaling were computed using only the subsets of overlapping days for each pair of observatories. Because of the significant 14 year gap in observations, two subsets from the Sayan observatory (station No. 5) were treated as two independent data sets: one set included observations from 1964 to 1967 and from 1970 to 1971 and the second one included observations from 1985 to 1995. The newer observations (from 1998 to 2011) from the Crimean observatory were added to the unified data set shown in Figure 3.

4. DISCUSSION

Figure 4 shows the annual average of sunspot field strengths derived from the unified data set of the seven observatories. The data span four and a half solar cycles from the maximum of Cycle 19 to the rising phase of Cycle 24. The sunspot field strengths exhibit cyclic variations reaching maxima around the peak of each cycle although the synchronicity is not absolute. In Cycle 19, the sunspot field strength reached a maximum about two years after the maximum in sunspot numbers. For Cycle 21, maximum in sunspot numbers and the maximum sunspot field strength are displaced by about three years (Figure 4). On average, the decrease in the sunspot field strength during the declining phase of each cycle is about 500–600 G. Fitting the linear polynomial to the monthly averages of the declining phase of each cycle yields the following gradients in field strength (in units of G year^{-1}): -83.5 ± 21.4 (Cycle 19), -47.1 ± 8.9 (Cycle 20), -97.9 ± 10.0 (Cycle 21), -85.1 ± 6.4 (Cycle 22), and -118.7 ± 7.9 (Cycle 23). The numbers are larger than the ones reported by Penn & Livingston (2006): -52 G year^{-1}; and by Watson et al. (2011): -70 G year^{-1} for the declining phase of Cycle 23. This difference can be attributed to differences in the observations and the data analysis. In comparison with other cycles, the decrease in the sunspot field strength appears to be stronger for the declining phase of Cycle 23. However, one should note that the data for Cycles 19–22 are averages from several observatories, while Cycle 23 is represented by the data from a single observatory. The latter may account for some gradient differences of the field strengths. Qualitatively, the amplitudes of gradients of sunspot magnetic field strengths do not appear to correlate well with the amplitude of a solar cycle or the steepness of the declining phase of the cycle (Figure 4). For example, judging by the sunspot numbers, Cycle 23 was similar to Cycle 20 (compare sunspot numbers for Cycle 23 overplotted on Cycle 20 in Figure 4). On the other hand, the amplitude of the gradient of the magnetic field strengths for the declining phase of Cycle 23 is about twice the gradient observed in Cycle 20. Most importantly, our data show no indication of a secular trend (either decreasing or increasing with time) over four and a half solar cycles covered by these synoptic observations. A trend reported by Penn & Livingston (2006, 2010) could be associated with the decrease in the sunspot field strength during the declining phase of Solar Cycle 23. The recent study by Lozitska (2010) had reported a gradual increase in the field strengths between 1970 and 1990 measured at the Crimean observatory. Such an increase can be seen in Crimean raw data shown in Figure 1 (blue line). In our opinion, this increase may be related to a varying contribution of weaker field strength solar features (pores and small umbrae) caused by changes in instrumentation in 1966 and early 1970s. Monthly and yearly averages of daily strongest field strengths (Figures 3 and 4) do not show any noticeable secular trend.

Our results suggest that the solar dynamo produces sunspots with noticeably larger field strengths near the maximum of the sunspot cycle. Studies of solar rotation had indicated a dependency between the solar rotation rate and the active region size/field strength (e.g., Javaraiah & Gokhale 1997). Such dependency was interpreted as an indication that active regions with stronger magnetic fields originate deeper in the convection zone compared with the weaker field regions (Gilman & Foukal 1979; Sivaraman & Gokhale 2004). This (together with our findings) may suggest that in each cycle the formation of active regions begins at some intermediate depths in the convection zone, and as the solar cycle progresses the depth of sunspot formation moves deeper in the convection zone. At the declining phase of the cycle, the sunspot formation depth moves back to intermediate depths similar to the beginning of the solar cycle.

Although our statistical sample is very small for making a quantitative conclusion, we note a possible tendency for minima with a weaker sunspot field strength to be followed by a weaker sunspot cycle (compare plots of international sunspot numbers and the sunspot field strength in Figure 4). Thus, for example, the yearly averaged magnetic field strengths in minima of Cycles 19–22 were at 1959.2 G, 2308.7 G, 2287.5 G, and 2022.5 G, respectively. Cycles 20–23 that followed these minima had annual sunspot numbers (W) at 105.9, 155.4, 157.6, and 119.6, respectively. Applying a linear regression to these numbers yields a prediction for the maximum amplitude of Cycle 24 of $W_{\rm Cycle\,24} = 67 \pm 35$, which is within 1σ error bars of previous predictions (e.g., $W_{\rm Cycle\,24} = 92 \pm 13$; Tlatov & Pevtsov 2010 and references therein).

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