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ON A POSSIBLE EXPLANATION OF THE LONG-TERM DECREASE IN SUNSPOT FIELD STRENGTH

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ABSTRACT

Recent studies revealed a controversy in long-term variations in sunspot field strengths. On one hand, the sunspot field strengths computed by averaging both large and small sunspots and pores show a gradual decrease over the declining phase of solar Cycle 23 and the rising phase of Cycle 24. On the other hand, the strongest sunspot field strengths demonstrate only solar cycle variations with no long-term decline. Here, we investigate the field strength and area properties of sunspots in an attempt to reconcile the presence of both tendencies in recent sunspot field strength measurements. First, we analyze the data set from Penn & Livingston, and we show that in addition to the previously reported long-term decline, the data show the solar cycle variation when only sunspots with the strongest magnetic fields are included. Next, we investigate the variations in the number of sunspots of different sizes, and we find a negative correlation between the numbers of small and large sunspots. Finally, we show that during the period of 1998–2011, the number of large sunspots gradually decreased, while the number of small sunspots steadily increased. We suggest that this change in the fraction of small and large sunspots (perhaps, due to changes in the solar dynamo) can explain the gradual decline in average sunspot field strength as observed by Penn & Livingston.

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

1. INTRODUCTION

Cyclic variations of the relative sunspot and/or group number have been known since the beginning of the 17th century. The prevailing periodicity in solar cycle variations is about 11 years. In addition, variations with longer periods have been reported by many researchers. The most prominent are the 60–120 year (Gleissberg) cycle, the 205–210 year (Suess) cycle, and a 600–700 year and a 2000–2400 year cycles. The cyclic variations may be suppressed during prolonged periods identified as grand minima. The most prominent of the grand minima is the Maunder minimum during 1645–1715. Smaller "grand minima" took place in 1450–1550 (Spörer minimum) and 1790–1820 (Dalton minimum). A review of solar cyclic activity can be found in Usoskin & Mursula (2003).

Using the observations taken in the Fe I λ1564.8 spectral line from 1998 to the present, Penn & Livingston (2006, 2011) found a gradual decrease in the average values of the sunspot magnetic field strengths over the last few years. One can speculate that this long-term decrease may be heralding a new grand (Maunder-like) minimum.

On the other hand, Pevtsov et al. (2011), on the basis of observations from the synoptic solar program in the former USSR, found that the strongest magnetic fields of sunspots show cyclic, instead of secular, variations. The 11 year cycle variations associated with Cycles 23 and 24 are also evident in the Livingston–Penn data set if one considers the outer envelope of the data shown in Penn & Livingston (2011). Rezaei et al. (2012) confirmed that the cyclic variations of sunspot magnetic fields in 1999–2011 dominated over any long-term trend. Lozitskaya (2010) suggested that the gradual decline of sunspot field strengths reported by Penn & Livingston (2006) may be related to a non-homogeneity of observational data (i.e., fewer measurements of sunspots at the beginning of the series and increasingly more detailed observations in later years). In this Letter, we investigate the field strength and area properties of sunspots in an attempt to reconcile the presence of both the cycle variations of the strongest sunspot field strengths and a gradual decline in average field strengths when both large and small spots are averaged.

2. DATA SETS

The data used in our analysis come from three different sources: the field strengths measurements in near-infrared and visible spectral lines, and sunspot areas. The field strengths in near-infrared were measured in Fe I λ1564.8 at the National Solar Observatory at Kitt Peak (NSO/KP; for description, see Penn & Livingston 2006). Field strength was determined graphically from the separation of two components of the spectral line. In the following discussion, we refer to this data set as H_{LP}. The field strengths in the visible spectral range were observed in Fe I λ 630.2 at the Crimean Astrophysical Observatory (CrAO) as part of their synoptic program (see http://solar.crao.crimea.ua/data/sunspots/). This second data set is referred to as H_{CR}. H_{CR} is similarly measured, using the separation between two σ components of the spectral line (for description, see Pevtsov et al. 2011). Sunspot areas (A) are measured using the digitized photoheliograms of the Sun taken in white light at the Kislovodsk Mountain Astronomical Station of Pulkovo Observatory (http://158.250.29.123:8000/web/Soln_Dann/).

3. SUNSPOT MAXIMUM MAGNETIC FIELDS

First, we apply the same selection criteria as in Pevtsov et al. (2011) to both H_{LP} and H_{CR} measurements. In this approach, we analyze all sunspots observed each day, but we record only the one sunspot per day with the strongest field strength. The approach allows for a better comparison between two observing sites with different atmospheric seeing, and it mitigates a potential observer's bias.

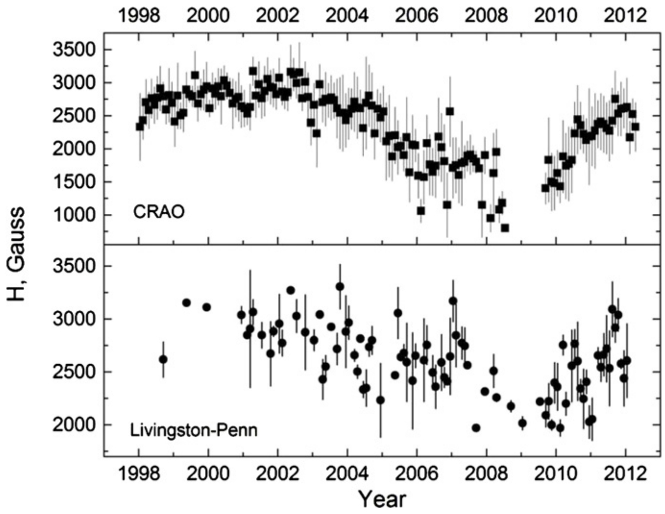

Figure 1. Monthly averages (filled circles) of the strongest field strengths selected from H_{CR} (top) and H_{LP} (bottom) data sets. The vertical segments show 1σ standard deviation.

The monthly means of these daily sunspot peak measurements (Figure 1) indicate a good correlation between the two sets of measurements (H_{LP} and H_{CR}), albeit with a different level of scatter and different scale in field strengths. Most importantly, both data sets show a gradual decrease in the field strengths over a period of about nine years (2000–2009) followed by increase from 2009 to 2012. These changes follow the solar Cycles 23 and 24 and are in agreement with the Pevtsov et al. (2011) results.

Based on this strong correlation between the two field strength measurements (Pearson correlation coefficient $\rho = 0.83$ as computed for annual averages), we established the following linear relationship between H_{LP} and H_{CR}:

$$H_{LP} = (0.425 \pm 0.079) \cdot H_{CR} + (1690 \pm 180). \qquad (1)$$

Figure 2 (left) compares H_{CR} and H_{LP} converted to the H_{CR} system using Equation (1). Figure 2 (right) shows the annual averages of H_{LP} (in H_{CR} system) plotted over the data from Pevtsov et al. (2011). It is clear that the cycle variations are also present in H_{LP} data if the data are limited to the daily strongest field measurements. The presence of a gradual decrease in average values of H_{LP} (see Penn & Livingston 2011) and the cycle variation in H_{LP} for strongest sunspot fields (Figure 2) suggests a possible change in the distributions of sunspots with weak and strong fields during the period of declining phase of Cycle 23 and the rising phase of Cycle 24. To investigate this hypothesis, we now turn to the analysis of sunspot areas.

4. SUNSPOT AREAS

Early investigations by, e.g., Nicholson (1933), Houtgast & van Sluiters (1948), and Ringnes (1965) have established the presence of a statistical dependency between the sunspot magnetic field strength and sunspot total area. Various forms of functional dependencies were studied, but all show a strong correlation between the field strength in sunspots and the total area of the sunspot (typical Pearson correlation coefficient $\rho =$ 0.7–0.8). Comparing the different functional dependencies, Ringnes & Jensen (1960) concluded that a log-linear relation between the sunspot area and the field strength is more representative of the data. Here we investigate the properties of sunspot areas with the understanding that there is a correlation between the area of sunspots and their field strengths (i.e., larger sunspots tend to have stronger field strength). Figure 3 shows the distribution of the total area of sunspots (including penumbra) in logarithmic scale as observed at the Kislovodsk Mountain Astronomical Station. The distribution of the logarithm of the areas shown in Figure 3 can be represented by a combination of two normal distributions. The latter indicates the presence of two populations of sunspots. In the following discussion, we refer to these two populations as "small" and "large" spots. The existence of two lognormal populations in the sunspot area distributions was reported by several authors (see, e.g., Kuklin 1980 and references therein). All these previous studies, however, were based on the analysis of the total area of groups, while here we use the total area of individual sunspots.

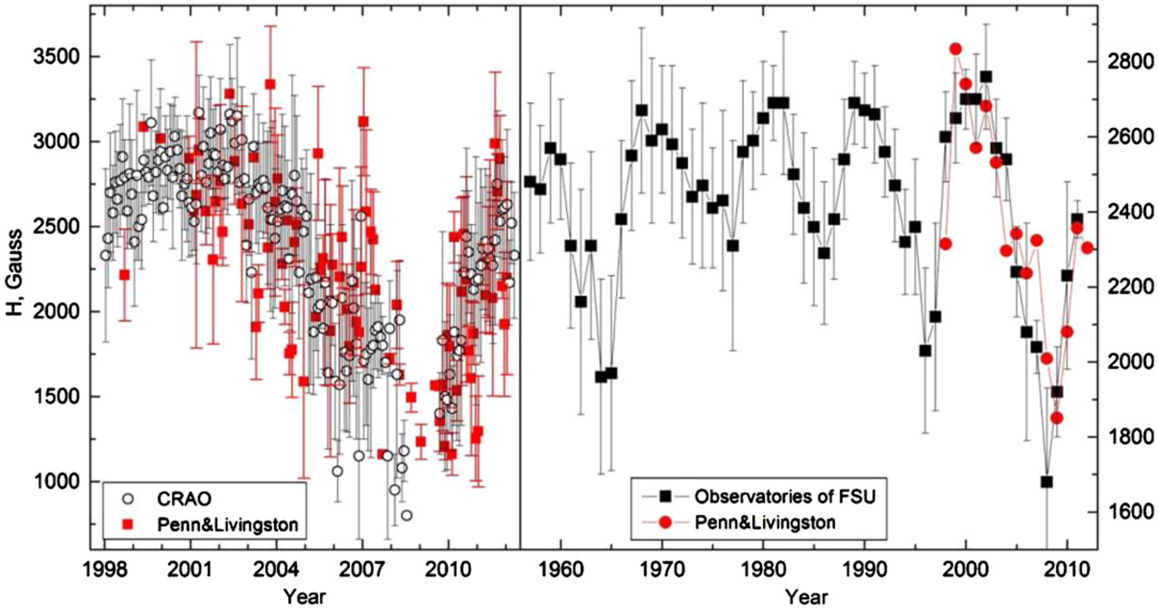

Figure 2. Left: monthly averages of the magnetic field strength H_{CR} (black open circles with error bars) and H_{LP} converted to H_{CR} system (red filled squares with error bars). Right: annual values of H_{LP} (in H_{CR} system) are shown as filled red circles with error bars and data from Pevtsov et al. (2011) are shown in black.

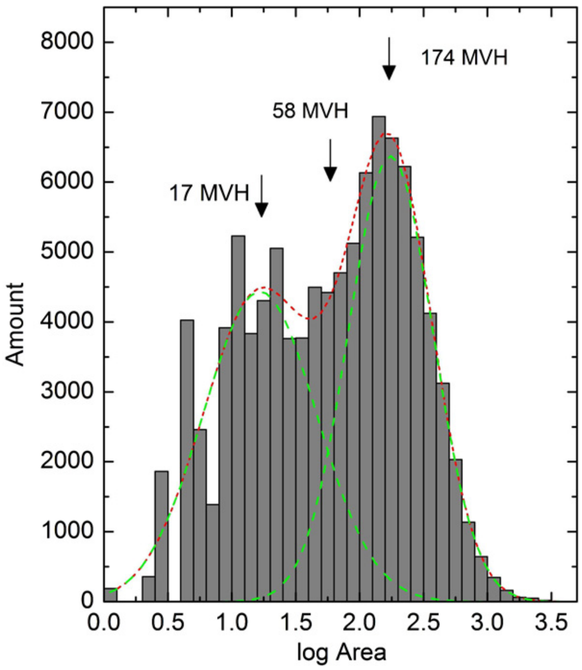

Figure 3. Statistical distribution of logarithm of sunspot areas (*A*, in millionth of visible hemisphere, MVH) as measured at the Kislovodsk Mountain Astronomical Station. Dashed green line represents two Gaussian functions fitted to the observed distribution. Red line shows a combined profile. Arrows mark the mean values of areas (corresponding to the Gaussian functions) and the "saddle" between two Gaussian peaks.

Since the two populations overlap in their size distribution, we separate the sunspots into four categories as follows.

1. SS (smallest spots), $A \leqslant 17$ MVH (where A is area in millionth of the Sun's visible hemisphere—MVH).
2. SL (mostly small spots with a minor contribution from large spots), 17 MVH $< A \leqslant 58$ MVH.
3. LS (mostly large spots with a minor contribution from small spots) 58 MVH $< A \leqslant 174$ MVH.
4. LL (largest spots) $A > 174$ MVH.

These area criteria were chosen based on the properties of the distribution shown in Figure 3. Still one can note that in a recent paper Lefévre & Clette (2011) used an independent set of arguments to arrive at the same criterion for small spots ($A \leqslant$ 17 MVH).

The number of sunspots in each category varies with the sunspot cycle, but the cycle variations are different (Figure 4). For example, it is well established (e.g., from the international sunspot number or other indices of solar activity) that Cycle 19 is the strongest of all recent cycles. However, for intermediate-size sunspots (SL and LS categories), Cycle 19 has a lower amplitude than Cycle 21. Similarly, based on various indices of solar activity, Cycle 20 is lower in amplitude than Cycle 21. Contrary to that, the number of small sunspots (SS category) is larger in Cycle 20 as compared to Cycle 21. This difference in cycle variation of the number of sunspots with different areas suggests that the fractional distribution of sunspots by their size may change from one cycle to the other. Indeed, the change in fractional distribution of sunspots with different Zurich classes (and sizes) for Cycles 23 and 24 was recently reported by Lefévre & Clette (2011).

Figure 5 shows the variation of the fraction of sunspots of different categories during 1957–2011. Several long-term trends are clear. For example, during ≈1960–1975, the fraction of the smallest (SS) sunspots is above its average (26.5% ± 0.07%). During the same period, the fraction of the largest (LL) sunspots is below its average (25.3% ± 0.06%). A similar pattern can be seen around year 1995. Beginning 2006–2007, the fraction of SS sunspots increases, while the fraction of LL sunspots steadily decreases. In comparison, the intermediate-size sunspots (SL and LS categories) show much smaller variations. Furthermore, the changes do not appear to correlate well with changes in other sunspot size categories. Thus, for example, the changes in the fraction of largest (LL) sunspots show a strong negative correlation with the fraction of the smallest (SS) sunspots (correlation coefficient $\rho = -0.786$). The variations in sunspots of intermediate (SL and LS) size do not correlate with the LL or SS sunspots (LL–SL and LL–LS correlation coefficients are $\rho = -0.062$ and $\rho = 0.066$ respectively). We speculate that this long-term change in the fraction of sunspots of different sizes is at the core of the gradual decrease in the average sunspot field strength reported by Penn & Livingston (2006, 2011).

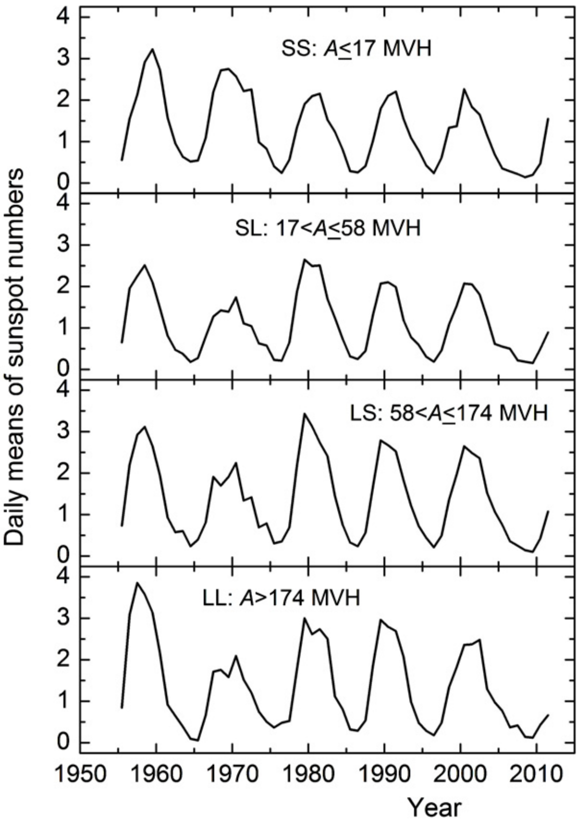

Figure 4. Time variation of annual averages of daily number of sunspots of different size categories. SS and LL categories correspond to smallest and the largest sunspots; SL and LS categories represent sunspots of an intermediate size.)

5. DISCUSSION

We examine the observations of sunspot field strength in the near-infrared Fe 1564.8 nm spectral line from 1998 to present. The annual averages of these data, when both large and small sunspots are averaged, show a long-term decline (e.g., Penn & Livingston 2011). On the other hand, when we restrict the data set to the strongest field measurements as in Pevtsov et al. (2011), we find only solar cycle variations (Figure 1). To reconcile the presence of both the long-term and the 11 year cycle trends in the data, we analyze the areas of sunspots. By

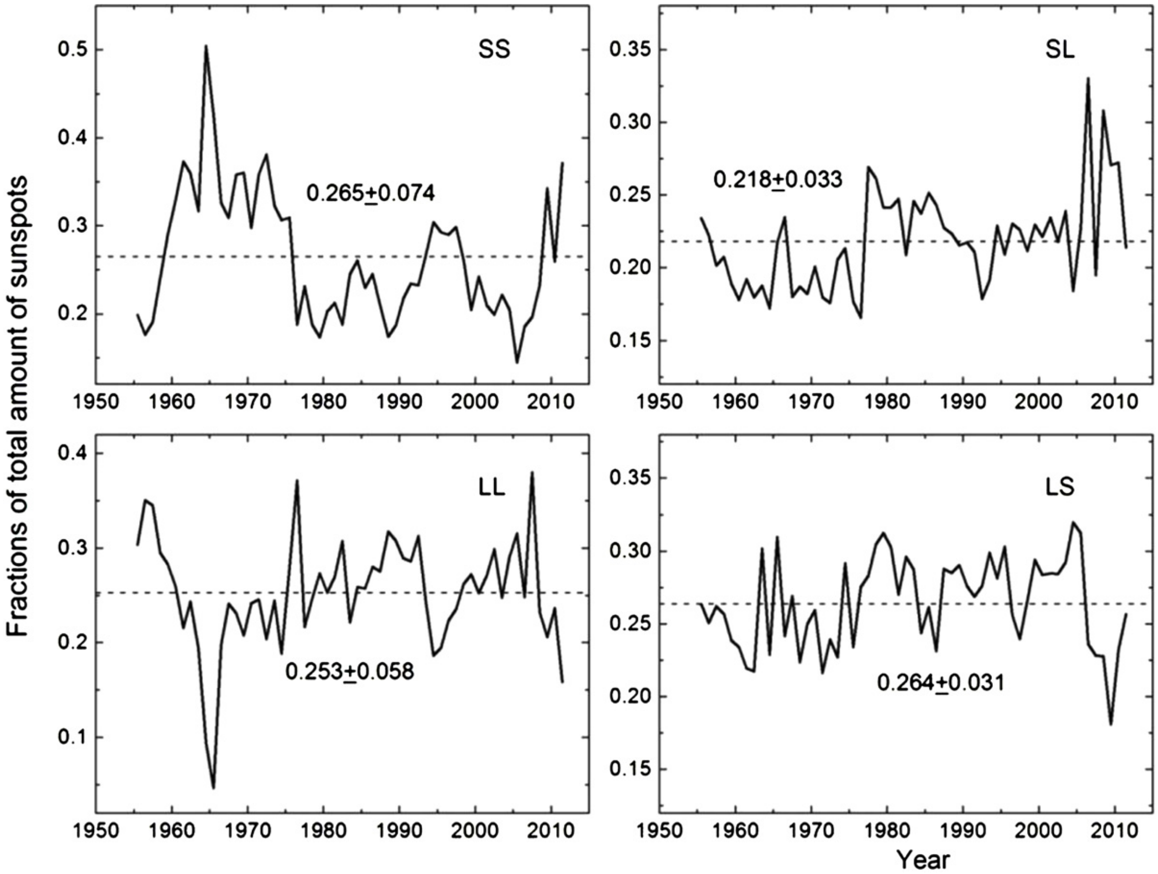

Figure 5. Time variations of fractions in total amount sunspots for different categories. Dotted lines show an average fraction for each given population. The numbers represent the values of the mean fraction and their standard deviations.

segregating the sunspots into four categories based on their size, we show that the fraction of the smallest and largest spots changes between different sunspot cycles in a systematic way: When the number of small sunspots increases, the number of large spots decreases. The fraction of intermediate-size sunspots does not show any coherent variations that correlate with the number of small and large spots. Therefore, we suggest that a gradual decrease in average field strength over the last decade can be explained by a decrease in the fraction of large sunspots with stronger magnetic fields and a corresponding increase in the fraction of small spots with weaker fields (Figure 5). When applying a known correlation between the area of sunspots and magnetic field strength, this increase in the fraction of small sunspots implies a gradual decrease in the average field strength when both large and small sunspots are averaged together. The latter is in qualitative agreement with the Penn & Livingston (2011) findings.

The presence of two (“small” and “large”) categories of sunspots (as based on their areas) and the difference in the cycle variations of these two categories appear to be more in line with the distributed dynamo models, when the sunspots are formed in different layers throughout the convection zone (e.g., Brandenburg 2005). One would expect that a dynamo operating in a narrow tachocline at the base of the convection zone would produce a more uniform distribution of sunspots of a different size.

A change in the proportion between the small and large sunspots may have another important consequence. Suppose that during a grand solar minimum (e.g., Maunder minimum) the sunspots do not vanish all together, but only the large sunspots disappear. This change would not require the complete shutdown of the solar dynamo. Only the depth dependence of the dynamo will change, and it would favor the production of small sunspots. From an observational perspective, the smallest sunspots are much harder to detect, especially with the visual observations conducted with relatively poor telescopes, which could explain the low sunspot counts during some of the past grand minima. Furthermore, modern observations suggest that the smaller sunspots are less likely to be associated with flare and coronal mass ejection activity, and thus, the magnetic fields on smaller scales may have a reduced effect on the amount of the magnetic field expelled to the heliosphere. The latter may affect the secondary proxies of the solar activity (e.g., cosmic-ray flux and frequency of aurorae) that are often used as additional identifiers of the Maunder minimum. This possibility that the grand minima in solar activity can be related to changes in size of sunspots produced by the dynamo should be explored further, for example, by means of existing numerical dynamo models and via a detailed analysis of the historic sunspot field strength measurement.

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REFERENCES

Brandenburg, A. 2005, ApJ, 625, 539
Houtgast, J., & van Sluiters, A. 1948, Bull. Astron. Inst. Neth., 10, 325
Kuklin, G. V. 1980, Bull. Astron. Inst. Czech., 31, 224
Lefévre, L., & Clette, F. 2011, A&A, 536, L11
Lozitskaya, N. I. 2010, Kosmichna Nauka Teknologia, 16, 30
Nicholson, S. B. 1933, PASP, 45, 51
Penn, M. J., & Livingston, W. 2006, ApJ, 649, L45
Penn, M. J., & Livingston, W. 2011, in IAU Symp. 273, The Physics of Sun and Star Spots, ed. D. Choudhary & K. Strassmeier (Cambridge: Cambridge Univ. Press), 126
Pevtsov, A. A., Nagovitsyn, Y. A., Tlatov, A. G., & Rybak, A. L. 2011, ApJ, 742, L36
Rezaei, R., Beck, C., & Schmidt, W. 2012, A&A, 541, A60
Ringnes, T. S. 1965, Astrophys. Nor., 10, 27
Ringnes, T. S., & Jensen, E. 1960, Astrophys. Nor., 7, 99
Usoskin, I. G., & Mursula, K. 2003, Sol. Phys., 218, 319