THE SUN’S SMALL-SCALE MAGNETIC ELEMENTS IN SOLAR CYCLE 23

C. L. Jin¹, J. X. Wang¹, Q. Song¹, and H. Zhao²

¹ Key Laboratory of Solar Activity of Chinese Academy of Sciences, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; cljin@nao.cas.cn, wangjx@nao.cas.cn
² Physics Department, National Tsing Hua University, Hsinchu, Taiwan; berserker0715@hotmail.com

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ABSTRACT

With the unique database from the Michelson Doppler Imager on board the Solar and Heliospheric Observatory in an interval embodying solar cycle 23, the cyclic behavior of solar small-scale magnetic elements is studied. More than 13 million small-scale magnetic elements are selected, and the following results are found. (1) The quiet regions dominated the Sun’s magnetic flux for about 8 years in the 12.25 year duration of cycle 23. They contributed (0.94–1.44) × 10¹⁹ Mx flux to the Sun from the solar minimum to maximum. The monthly average magnetic flux of the quiet regions is 1.12 times that of the active regions in the cycle. (2) The ratio of quiet region flux to that of the total Sun equally characterizes the course of a solar cycle. The 6 month running average flux ratio of the quiet regions was larger than 90.0% for 28 continuous months from July 2007 to October 2009, which well characterizes the grand solar minima of cycles 23–24. (3) From the small to the large end of the flux spectrum, the variations of numbers and total flux of the network elements show no correlation, anti-correlation, and correlation with sunspots, respectively. The anti-correlated elements, covering the flux of (2.9–32.0) × 10¹⁸ Mx, occupy 77.2% of the total element number and 37.4% of the quiet-Sun flux. These results provide insight into the reason for anti-correlations of small-scale magnetic activity during the solar cycle.

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

1. INTRODUCTION

No astrophysical process but the solar cycle leaves such massive footprints on the human living environment. This 11 year cycle was discovered by the German astronomer Samuel Schwabe (1843) through observation of the changes in the number of solar sunspots. A primary understanding of the solar cycle has been established based on the theories and simulations of a mean-field magnetohydrodynamic (MHD) dynamo (Charbonneau 2005). However, new observations are continuously challenging our understanding through myriad new and seemingly conflicting observations. A more severe challenge comes from observations of small-scale magnetic elements (see de Wijn et al. 2009). Therefore, exploring the physics of the solar cycle is still a difficult task.

Since the 1960s it has been observed that small-scale magnetic fields outside of sunspots are everywhere on the Sun (Sheeley 1966, 1967; Harvey 1971). The stronger magnetic elements at the boundaries of supergranulation cells are network elements, while the smaller and weaker elements within the supergranulation cells are intra-network (IN) elements (Livingston & Harvey 1975; Smithsonian 1975). Similar to emerging flux regions (ERs) in sunspot groups (or active regions) (Zirin 1972), small-scale emerging bipoles named ephemeral (active) regions (ERs) were described by Harvey & Martin (1973). These bipoles, along with the debris from decaying sunspots, account for the formation of network elements. It was noticed that the flux emerging rate in ERs exceeds that in sunspots by two orders of magnitude (Zirin 1987). Moreover, the flux generation rate of IN elements exceeds that of ERs by another two orders of magnitude. By present telescopes, further smaller magnetic fibrils are believed to be mostly unresolved yet their aggregation is the dominant mechanism by which IN and network elements appear (Lamb et al. 2008). A substantial amount of solar magnetic flux is probably still hidden (Trujillo Bueno et al. 2004).

Following identification of the small-scale magnetic elements, great efforts have been made to understand how they change during a solar cycle and if they are correlated with sunspots. Diverse observations have been reported, igniting discussions and debates in the literature. The observations were made either directly from the magnetic measurements or indirectly from proxies of small-scale magnetic flux, e.g., the G-band and Ca ii K bright points and coronal X-ray bright points. Key revelations are listed below:

1. No cyclic variations: Ca ii K emission in solar quiet regions (White & Livingston 1981), modern X-ray bright point (XBP) observations (Sattarov et al. 2002; Harra & Nakakubo 2003), magnetic flux of networks (Labonte & Howard 1982), flux spectrum and total flux of network elements with flux <2.0 × 10¹⁹ Mx (Hagenaar et al. 2003), and Stokes I profile (Trujillo Bueno et al. 2004).
2. Anti-correlation of small-scale fields with the sunspot cycle: The number of network bright points in very quiet regions (Muller & Roudier 1984, 1994), He i 10830 Å dark points in the higher chromosphere (Harvey 1985), early X-ray bright point observations (Davis et al. 1977; Davis 1983; Golub et al. 1979), and weak changes of emergence frequency of ERs with flux less than (3–5) × 10¹⁹ Mx (Hagenaar et al. 2003).
3. Correlation with the sunspot cycle: More ERs appeared during active solar condition (Harvey & Harvey 1974; Harvey 1989), the number (or magnetic flux) of network structures (Foukal et al. 1991; Meunier 2003), and flux distribution and total flux of network concentrations with flux ≥3.0 × 10¹⁹ Mx (Hagenaar et al. 2003).

The observations listed above are related to some fundamental, but not yet resolved questions in solar physics: the origin, dynamics, and active role in the Sun’s global processes of solar small-scale magnetic elements, as well as the controlling physics of the solar activity cycle. Discrepancies among
First, for the observations of the proxies of small-scale magnetic elements, the connections between the magnetic elements and their proxies are not well quantified, and the underlying physics is not known exactly. There does not seem to be a one-to-one correspondence between network elements and network bright points (Zhao et al. 2009). In other words, the widely adopted paradigm of “magnetic bright points” is still questionable. Moreover, the early revelation about the magnetic properties of coronal X-ray bright points (Golub et al. 1977; Webb et al. 1993) needs to be revisited and updated with state-of-the-art observations.

Second, many of the reports listed above went back to early solar observations. Rather poor resolution, calibration, and consistency in sensitivity in early magnetic measurements make evaluation of the quality of the observations difficult. As an example, the early Mount Wilson magnetograph observations (Labonte & Howard 1982) had a resolution of $\geq 12.5–17.5$ arc-sec, and the calibration was not consistent. We are simply not able to confidently comment on their conclusions. Additionally, early X-ray bright point measurements, which suffered from low cadence, are purported to show a decrease in the number of X-ray bright points in the solar cycle. More recent higher cadence observations have called into question whether this effect is real. Whether other observations of variation within the solar cycle also need to be reinterpreted remains to be seen. New observations with careful and thorough data reduction and interpretation are crucial.

Third, even for recent observations, different algorithms and logic in data analysis sometimes make it hard to judge the results. An interesting example comes from the analysis of full-disk magnetograms of the Michelson Doppler Imager on board the Solar and Heliospheric Observatory (MDI/SOHO) (Scherrer et al. 1995). By adopting a different detection algorithm and approaches, Muenier (2003) revealed correlation of the network element number (or flux) with sunspots. In contrast, Hagenaar et al. (2003) declared a weak anti-correlated emergence rate of ERs and an independence of the total absolute flux for smaller network concentrations. This discrepancy should be clarified with new analysis.

Claritying the problem and closing the debates are essential tasks in understanding the solar cycle phenomena. Fortunately, MDI/SOHO is now providing a unique database—full-disk magnetograms over more than 13 years, covering the complete 23rd solar cycle. The 13.5 year 5 minute average full-disk magnetograms are used in the current study. However, poor temporal resolution makes the identification of ERs questionable and the sensitivity of the full-disk magnetograms rules out the possibility of resolving the IN elements. Therefore, we have basically identified the network magnetic elements in this study.

In this paper, we aim at learning the cyclic variations of the quiet Sun’s magnetic flux and small-scale magnetic elements. Use of the full-disk MDI magnetograms with temporal coverage of the entire cycle 23 comes from an awareness of the intermittency of solar cyclic behavior in both the temporal and spatial domains. Because of this intermittency, selecting the magnetograms of a short interval, e.g., 10–30 hr, in a month from each year, at the “supposed” different cycle phases, would not guarantee a grasp of the key characteristics of a solar cycle. From our understanding, choosing the database that covers the entire cycle 23 is of overwhelming importance. The database for the current study is unique in the sense that it is the only space-borne magnetic measurement of the full Sun for which the consistency in sensitivity and resolution persisted for a cycle-long interval. As we are interested in the global behavior of small-scale magnetic elements, sampling network elements in a cycle-long temporal domain and in all different flux ranges (or strengths) is more important than selecting a few interrupted high-cadence sequences. Moreover, the magnetic elements with different flux (or size) may have different origins and characteristics, therefore we group all the network magnetic elements into different categories in accordance with their magnetic flux.

In Section 2, we describe the observations, technique of calibration, evaluation of noise level of the magnetograms, separation of active regions and the quiet Sun, and selection of network elements. In Section 3, we present the results of the cyclic behavior of quiet region magnetic flux and small-scale magnetic elements. In Section 4, we make comparisons with previous studies and consider the possibilities in understanding the network magnetic elements anti-correlated with sunspots. In Section 5, we draw conclusions.

2. OBSERVATIONS AND METHODS

The MDI instrument on board the SOHO spacecraft provides a full-disk magnetogram with a pixel size of 2″. In order to obtain a low noise level, only the 5 minute average magnetograms are selected for this study. We extract one observed full-disk magnetogram per day for a total selection of 3764 magnetograms from 1996 September to 2010 February, including the complete 23rd solar cycle. In order to further reduce the noise level, we apply a boxcar smoothing function to each magnetogram by a width of 6″ × 6″. There are two groups of authors who first pointed out the underestimation of magnetic flux in earlier MDI full-disk magnetogram calibration (Berger & Lites 2003; Wang et al. 2003). The magnetograms used in this study were retrieved after the 2008 December recalibration. For a better understanding of the cyclic behavior of solar minima of cycles 22 and 23, we extend the MDI data base by adding Kitt Peak full-disk magnetograms from 1996 August back to 1994 January. The data merging is made based on a least-squares fitting of the mean flux density of Kitt Peak magnetograms to that of MDI magnetograms for the common interval of 1996.

We estimate the noise level of these smoothed 5 minute average magnetograms according to the method described by Hagenaar (2001) and Hagenaar et al. (2003). Based on these magnetograms, we analyze the histograms of magnetic flux density. The core of the distribution function is fitted by a Gaussian function $F(x) = \frac{B_{\text{max}}}{\sqrt{2\pi}\sigma} \exp(-x^2/2\sigma^2)$, where the width $\sigma$ of the Gaussian function, about 6 Mx cm$^{-2}$, is defined as the noise level.

We assume that the observed line-of-sight magnetic flux density is a projection of the intrinsic flux density normal to the solar surface, so the magnetic flux density for each pixel is corrected (see Hagenaar 2001 and Hagenaar et al. 2003) as $B_{\text{cal}} = B_{\text{obs}}(\alpha)/\cos(\alpha)$. The angle $\alpha$ of each pixel is defined by $\sin(\alpha) = \sqrt{x^2 + y^2}/R$ where $x$ and $y$ are the pixel position referring to the disk center, at which $x$ and $y$ is equal to 0, and the $R$ is the solar disk radius. After the correction, the magnetogram shows the magnetic flux density normal to solar surface.

When the angle is greater than 60°, there are fewer and fewer magnetic signals due to the lower magnetic sensitivity and spatial resolution of MDI/SOHO magnetograms, and the magnetic noise level would increase according to the magnetic...
correction \(1/\cos(\alpha)\). Therefore, we only analyze those pixels with angle \(\alpha\) less than 60°, i.e., the region included by the black circle in the left panels of Figure 1. The flux density of the pixels with 60° \(\leq\ \alpha\ \leq\ 90°\) is set to zero.

For each smoothed and corrected full-disk magnetogram of MDI/SOHO, we apply a magnetic flux density of 15 Mx cm\(^{-2}\) as a threshold to define the active regions (ARs) and their surroundings and then create a mask for each magnetogram. These masks include many small clusters and isolated pixels, so only the islands with an area larger than 9 × 9 pixels are defined as the active regions (Hagenaar et al. 2003). Considering the active regions close to the edge of 60°, in order to avoid missing them in the automatic procedure, we always search the active regions in the solar disk with angle \(\alpha\) less than 70° first, as shown in the left panels of Figure 1. Thusly, the islands with an area less than 81 pixels within the 60° disk are still defined as the active regions if they have more than 81 pixels found within the 70° disk.

Two magnetograms within 70° from the disk center at approximately the solar maximum and minimum phases, respectively, are displayed in the left panels of Figure 1. On these retrieved magnetograms the selected ARs are masked by red curves. The criterion for selecting ARs appears from a visual examination to work well for the given cases. In the right panels of Figure 1 two selected sub-windows of the magnetograms are shown with contours outlining the network elements, which are selected by a procedure of automatic feature selection. The yellow and green contours outline the selected network elements that belong to the components of elements correlated and anti-correlated with sunspots in the solar cycle, respectively (see Section 3.2).

3. RESULTS

3.1. Cyclic Variations of Magnetic Flux of Solar Quiet Regions

In order to compare the cyclic variations of magnetic flux of active regions with that of quiet regions, we calculate their respective magnetic fluxes, which are shown in the left panel of Figure 2. The area ratio of quiet regions is also computed, shown by purple “+” symbols in the right panel of Figure 2. It is found that the quiet Sun contributed \((0.94–1.44) \times 10^{23}\) Mx flux from approximately the solar minimum to the maximum in cycle 23. The fractional area of quiet regions always exceeds 80% in the entire solar cycle 23, and decreased from the cycle minimum to the maximum by a factor of 1.2, although their total flux increased by a factor of 1.53; as a comparison, the active region flux increased by several orders of magnitude. The measurements confirm the global behavior of the quiet-Sun fields (see Meunier 2003 and Hagenaar et al. 2003). During the 12.25 years of cycle 23, from 1996 October to 2008 December (see http://www.ips.gov.au), the quiet Sun dominated the Sun’s magnetic flux for 7.92 years. The monthly average magnetic flux of the quiet Sun is 1.12 times that of active regions. The magnetic fields on the quiet Sun are a fundamental component of the Sun’s activity cycle, maintaining the Sun’s magnetic energy and Poynting flux at certain levels.
1995 1998 2001 2004 2007 2010

Year

0

1

2

3

4

Magnetic flux (10^23 Mx)

1995 1998 2001 2004 2007 2010

Year

0.3

0.6

0.9

Ratio

Figure 2. Left panel is the flux variations of ARs (cross symbols in black) and quiet Sun (“+” symbols in purple) in an interval including the entire 23rd solar cycle. The red curve represents the sunspot number changes in the cycle. The shaded columns are the statistical results based on the Kitt Peak full-disk magnetograms. The magnetic flux for quiet regions rises from 0.94 × 10^{23} Mx in 1995 December to 1.44 × 10^{23} in 2002 May, increasing by a factor of 1.53. The fractional quiet Sun area is shown by purple “+” symbols in the right panel. It decreases by a factor of 1.2 from the solar minima to maximum. The ratio of quiet-Sun flux to the total Sun’s flux, the flux occupation of the quiet Sun, is shown by purple “+” symbols in the right panel. The quiet-Sun flux has dominated the Sun’s magnetic flux for 7.92 years in the 12.5 year cycle 23.

It is interesting to notice that the ratio of the quiet Sun’s magnetic flux to solar total flux (referred to as the flux occupation by the quiet Sun), like sunspots, characterizes the course of a solar cycle. The occupation of 6 month running average magnetic flux by the quiet Sun is shown by purple “+” symbols in the right panel of Figure 2. The active region flux shown in the left panel answers for the variation in the sunspot cycle. However, for the quiet regions, the maximum occupation of magnetic flux marks the minima of solar cycles. For instance, in our data set, the maximum flux occupation of the quiet Sun, which was 96.0%, first happened in October of 1996 at the beginning of cycle 23. The later maxima happened from 2008 July to 2009 August. In 2008 December, the beginning of cycle 24, the maximum occupation reached 99.3%. The 6 month running average fractional flux of the quiet Sun was larger than 90.0% for 28 continuous months (from 2007 July to 2009 October), which characterizes the grand solar minima of cycles 23–24. Staying at such a low activity level, there were 25 months for which the total AR flux was less than 10^{22} Mx. However, during the minima of cycles 22–23 for only 7 intermittent months, i.e., from 1995 December to 1996 April and from 1996 December to 1997 January, we witnessed a fraction larger than 90.0%. The distinction between the two solar minima is severe. This can be seen very clearly in Figure 2.

3.2. Cyclic Variations of Network Magnetic Elements

After excluding the ARs, we apply the magnetic noise, i.e., 6 Mx cm^{-2}, as a threshold to create a mask for each quiet magnetogram and define these magnetic concentrations with more than 10 pixels in size as network magnetic elements (Hagenaar et al. 2003). More than 13 million network elements have been identified for the interval from 1996 September to 2010 February. The probability distribution function (PDF) of these magnetic elements in the studied interval is shown in Figure 3 as the average flux distribution. The figure shows that the distribution of magnetic flux of network magnetic elements mainly concentrates at the flux of 10^{19} Mx. This peak distribution is consistent with that found for multiple MDI full-disk data sets by Parnell et al. (2009).

For an exclusive examination, we divide all the magnetic elements into 96 sub-groups according to the flux per element. In this way, a statistical sample is created, covering the range of magnetic flux per element from the smallest observable network flux of 1.5 × 10^{18} Mx for the current data set to an upper limit of 3.8 × 10^{20} Mx. The monthly variation of magnetic elements for each sub-group is calculated and examined in terms of number density and absolute total flux in the interval from 1996 October to 2010 February, embodying the entire cycle 23. The influence of the area changes of the quiet Sun on both quantities has been removed. There are 0.3% of network elements (or clusters) with flux larger than the upper limit; these were fragments of decayed sunspots and are not included in the sample. Following Hagenaar et al. (2003), tiny flux pieces with less than 10 pixels are not considered in the study. As a whole the total flux of these tiny flux pieces showed a small variation in the scope of (3.5–4.0) × 10^{22} Mx during the cycle.

The correlation coefficients between the cyclic variation of numbers of network elements and sunspots are calculated for...
and reach as high as 0.92 after a very narrow transition in the flux range of number in sub-group vectors for each sub-group element. Denoting the element each sub-group of network elements and shown in Figure 4. Figure 4. Correlation coefficients between the sunspot number and network elements and the sunspot cycle: no correlation, anti-correlation, and correlation. At the low end of the flux spectrum, there are very small correlation coefficients. With the increasing flux per element, the correlation, and correlation. This behavior is held for both the work elements and the sunspots: basically no correlation, anti-correlation to correlation takes place between (3.20 and 4.27) × 10^{19} Mx. The correlated component elements have magnetic elements in accordance with the flux range listed in the table. The detailed cyclic variations of each category of network elements are shown in Figure 5.

Each sub-group of network elements and shown in Figure 4. They are the linear Pearson correlation coefficients of two vectors for each sub-group element. Denoting the element number in sub-group i as N_{i} and the sunspot number N_{s}, the correlation coefficient between N_{i} and N_{s} will be

$$\rho(N_{i}, N_{s}) = \frac{\text{Covariance}(N_{i}, N_{s})}{\text{Variance}N_{i} \times \text{Variance}N_{s}}^{\frac{1}{2}}.$$  

(1)

The confidence level for the correlation can be found in some basic statistics handbooks, taking into account the size of the sample. The sample size for each sub-group element is 162, which is quite large. If the coefficient is higher than 0.256, then the failure probability of the linear correlation would already be <0.001.

From the small to the large flux spectrum, there appears a remarkable three-fold correlation scheme between the network elements and the sunspots: basically no correlation, anti-correlation, and correlation. This behavior is held for both the element number and total flux. Anti-correlation and correlation have been observed at a very high confidence level. The majority of the correlations show a failure probability ≤0.001. Between anti-correlation and correlation, there is a narrow range of magnetic flux per element of (3.2–4.3) × 10^{19} Mx. Network elements falling in this flux range show a transition from anti-correlation to correlation with the sunspot cycle (see the narrow shaded column in the middle of Figure 4.)

The dependence of the correlation coefficient on the element flux hints at the possibility that network elements at different segments of the flux spectrum may present different physical origins and different cyclic behavior accordingly. For a detailed examination of cyclic behavior of network elements, we group all the network elements into four categories which show, respectively, no correlation, anti-correlation, transition from anti-correlation to correlation, and correlation with the sunspot cycle. For each category, its flux range, percentage in number and in total flux, and correlation coefficient with sunspots are listed in Table 1. We then discriminate the cyclic variation of magnetic elements in accordance with the flux range listed in the table. The detailed cyclic variations of each category of network elements are shown in Figure 5.

Approximately 77.2% of the magnetic elements, covering the flux range of (2.9–32.0) × 10^{18} Mx, show anti-correlation with the sunspot cycle. This anti-correlated component contributed 37.4% of network flux during cycle 23. Transition from anti-correlation to correlation takes place between (3.20 and 4.27) × 10^{19} Mx. The correlated component elements have magnetic flux larger than 4.27 × 10^{19} Mx. They occupy approximately 15.7% in number but 53.5% of total flux of network elements. In the flux range of (1.5–2.9) × 10^{18} Mx, network elements show randomly independent variation with the sunspot cycle. From this data set, they occupy less than 0.6% of network elements and have neglectable total flux. With the poor sensitivity in flux measurements at the smallest end of the flux spectrum, we cannot exclude that the non-correlation component manifested some random noises in flux measurement. More serious efforts with higher resolution and sensitivity data are necessary to clarify the cyclic behavior of the smallest observable magnetic elements.

The number changes in the network elements in the flux range of (2.9–32.0) × 10^{18} Mx show obviously anti-phase correlation with the sunspot cycle, as do the changes of their total unsigned flux. However, the cyclic minimum of this anti-correlation component does not exactly coincide with the reversed profile of the maximum of the sunspot cycle, implying complexity in the cause of the anti-correlation. Meanwhile, the flux changes of the magnetic elements with flux larger than 4.3 × 10^{19} Mx show remarkable in-phase correlation with the sunspot cycle. The profiles of the maximum of network elements and of sunspots do not correspond to one another exactly. There is a 5–7 month delay in their cyclic maximum related to that of the sunspot cycle. This seems to be related to the characteristic dispersal time of active region fields.

To further explore the cyclic variation of magnetic elements, we obtain the PDFs of yearly network magnetic elements.

Table 1
Cyclic Variation of the Network Elements in Different Flux Ranges

| Category       | Flux (in Mx) | Number ratio | Flux (ratio) | Cor.   |
|----------------|--------------|--------------|--------------|--------|
| No Correlation | (1.5–2.9) × 10^{18} | 0.58%        | 6.48 × 10^{21} (0.05%) | −0.04 |
| Anti-correlation | (2.9–32.0) × 10^{18} | 77.19%       | 4.72 × 10^{24} (37.40%) | −0.45 |
| Transition     | (3.20–4.27) × 10^{19} | 6.59%        | 1.15 × 10^{26} (9.08%) | −0.03 |
| Correlation    | (4.27–38.01) × 10^{19} | 15.65%       | 6.74 × 10^{25} (53.46%) | 0.82 |
Figure 5. Cyclic variations of network element number (right panel) and flux (left panel) of four categories of network elements shown in Table 1, which represents the three-fold correlation scheme of network elements with the sunspot cycle. The green “+” refers to anti-correlation component elements, while the purple “+” denotes the correlation component elements. Black and blue dotted lines are elements which have no correlation or shown transition from anti-correlation to correlation with the solar cycle.

according to the magnetic flux and compute the differential PDFs, i.e., the difference between the yearly PDFs and average PDF (see Figure 3). Here, the differential PDF is abbreviated as DPDF. We plot the DPDFs and show the variation for the magnetic flux spectrum from 1996 to 2010 in Figure 6. From this figure, we confirm the three-fold scenario of cyclic variations of network elements.

From the solar minimum to the solar maximum (see the first column of Figure 6), the distribution of magnetic elements in the flux range about \((3–30) \times 10^{18} \text{ Mx}\) gradually decreases, which shows anti-correlation with the sunspot cycle; while the distribution of magnetic elements of flux larger than about \(4 \times 10^{19}\) shows correlation with the sunspot cycle and reaches a peak in the years 2000, 2001, and 2002. Furthermore, the distribution of magnetic elements with flux of \(\sim 3 \times 10^{19}\) and less than \(3 \times 10^{18} \text{ Mx}\) shows almost no variation. The distribution of magnetic elements correlated with the sunspot cycle reaches the smallest values in the years 2007, 2008, and 2009, which are the solar minima of cycles 23–24; while the distribution of magnetic elements anti-correlated with the sunspot cycle shows an outstanding peak during this long interval (see the third column of the figure). This distribution characterizes the long duration of the solar minima of cycles 23–24. The distributions in some of the ascending and declining phases (see that in 1998 and 2005) more or less represent the average distribution of small-scale magnetic elements shown in Figure 3.

4. DISCUSSION

With the unique space-borne observations that comprise a complete solar cycle, we have revealed a three-fold scheme of correlation of the Sun’s small-scale magnetic elements with the sunspot cycle and identified an anti-correlation component of network elements that dominates the element population. Before presenting our conclusion and discussion on the physics, a comparison with previous studies that adopted similar approaches and with that same space-borne MDI observations (see Section 2) is necessary.

Hagenaar et al. (2003) selected high-cadence magnetograms of six time sequences, each of which covered 10–30 hr in a month from 1996 to 2000. These authors found that the component of network elements with flux \(\geq 30 \times 10^{18} \text{ Mx}\) varied in phase with the sunspot cycle. The magnetogram calibration they adopted had underestimated the flux density by a factor of about 1.6 (Bergers & Lites 2003; Wang et al. 2003). With the renewed calibration, this component would consist of magnetic elements with flux \(\geq 4.8 \times 10^{19}\). This is a component in our analysis that changes in phase with sunspots. Meunier (2003) chose strong magnetic elements with threshold flux density of 25 G and 40 G, respectively, and found a natural correlation of number and flux of network elements with sunspots.

With element flux \(\leq 20 \times 10^{18} \text{ Mx}\) (i.e., \(32 \times 10^{18} \text{ Mx}\) in renewed calibration), Hagenaar et al. (2003) declared that both the flux spectrum of quiet network elements and the total flux changed a little with the cycle phase. In using the interrupted data in the 6 years of the ascending cycle phase, these authors would not be able to guarantee a grasp of the real trend of the cyclic modulation. We tested their results by using the same 6 month 5 minute magnetograms and found a weak change, anti-phased with the cycle phase, in both numbers and flux for network elements in this flux range. In fact, Hagenaar et al. (2003) reported that the number density of network concentrations on the quiet Sun decreased by less than 20% from 1997 to 2000, consistent with our approach. They also suggested an even anti-correlated change in flux emergence rate in this low flux range. The revelation of a remarkable anti-correlation component of network elements with a broad flux range from several times of \(10^{18} \text{ Mx}\) to \(3 \times 10^{19}\) Mx is likely to be the true nature of small-scale solar magnetism and inspire new considerations of the Sun’s magnetism.

Exploration of the magnetic nature of the Sun’s small-scale activity goes back to earlier solar studies. A few pioneer studies still stand as reliable references in solar physics. Mehltretter (1974) identified that the network bright points represented magnetic flux concentration with field strength of 1000–2000 G,
Figure 6. Differential probability distribution function (DPDF), i.e., the difference between the PDFs of yearly network magnetic elements and average PDF shown in Figure 3.

Observationally, small-scale network elements come from several sources: fragmentation of active regions, flux emergence in the form of ERs, coalescence of IN flux, and products of dynamic interaction among different sources of magnetic flux. The three-fold relationship between network elements and the sunspot cycle has immediate implications for the Sun’s magnetism. As demonstrated by state-of-the-art simulations (see Vögler & Schüssler 2007), the magnetic elements at the smallest end of the flux spectrum, either resolved or unresolved, manifest a local turbulent dynamo that operates in the near-photosphere and is independent of the sunspot cycle. On the other hand, at the larger flux end, the magnetic elements are likely to be the debris of decayed sunspots. They, of course, follow the solar cycle.

The key issue here is how to understand the majority of magnetic elements that are anti-correlated with sunspots in the solar cycle. They are likely not the debris of decayed sunspots but are probably created by turbulent local dynamo action that is globally affected or controlled by the sunspot field from the mean-field MHD dynamo. A few possibilities are now being considered.

First, during the more active times of the Sun, the smaller magnetic elements created by the turbulent dynamo have more
opportunity to encounter sunspots and their fragments. The same-polarity encounter results in a merging of those elements to the flux related to sunspots. The opposite-polarity encounter causes flux cancellations with the net result of lost smaller elements and a diffusion of sunspot flux. What accompanies the sunspot flux diffusion is reduced smaller elements with a turbulent origin. This possibly accounts for the anti-correlated magnetic component. By this kind of interaction, magnetic flux from turbulent dynamo actively takes part in the operation of the solar cycle, helping with more efficient magnetic diffusion. To quantify this mechanism, studies of dynamic interaction between small-scale magnetic elements and AR fields are crucial.

Second, it is also possible that at the solar maximum, the stronger magnetic field from sunspots tends to suppress the Sun’s global convection in some measure. As a result, the local dynamo has been abated somehow, and the network elements created by turbulence are reduced in number and total flux. This seems to suggest that the turbulent dynamo is, in fact, global but not local. Unfortunately, so far there have been no definite observations about the changes in the global solar convection during the sunspot cycle.

Another possibility is that the anti-correlated component represents the recycling of parts of the previously diffused or submerged magnetic flux from the mean-field dynamo (Parker 1987). The diffusion of magnetic flux from sunspots to the deep convection zone requires 5–7 years (Jiang et al. 2007). Parts of the diffused or submerged flux serve as the seed field for the globally turbulent dynamo. Its production is naturally out of phase with sunspots in the solar cycle and brings up the magnetic elements that are anti-phased with sunspots.

In recent research, Thomas & Weiss (2008) proposed a picture of the solar dynamo on three scales (one large and two small), which, according to the authors, were only loosely coupled to one another. It is not clear if some unknown interplay of different scale dynamos may result in the complicated behavior of the Sun’s small-scale fields. If we adopt the common vision that the smaller magnetic elements are created by a local turbulent dynamo, then the local turbulent dynamo on a certain scale must be closely correlated to the global mean-field dynamo. The global dynamo either provides seed flux or modifies the condition for this “global” turbulent dynamo. At the smallest end, the dynamo is likely to be more “local.” The turbulent dynamo, either global or purely local, brings to the Sun a tremendous amount of turbulent flux that continuously interacts with the products of the mean-field dynamo. The interaction seems to not only help with the operation of the global dynamo, but also power ceaseless small-scale magnetic activity and maintain the Sun’s Poynting flux to Earth and interplanetary space.

5. CONCLUSION

With the unique database from MDI/SOHO in the interval from 1996 September to 2010 February, which embodies the entire solar cycle 23, we analyze the cyclic variations of the quiet Sun’s magnetic flux and small-scale magnetic elements.

The quiet regions contributed (0.94–1.44) × 10^{23} Mx flux from approximately the solar minimum to maximum in cycle 23. The fractional area of quiet regions decreased from the cycle minimum to maximum by a factor of 1.2, but their total flux increased by a factor of 1.53. The quiet regions dominated the Sun’s magnetic flux over 60% of the duration of the cycle. Furthermore, the ratio of the quiet region magnetic flux to the Sun’s total flux can be used to describe the course of solar cycle, just as sunspots can. The maximum flux occupation of quiet regions marks the minima of solar cycle. The flux occupation on the quiet Sun was larger than 90% for 28 continuous months from 2007 July to 2009 October, which seems to equally characterize the grand minima of cycles 23 and 24.

With increasing magnetic flux per element, the number and total flux of the Sun’s small-scale magnetic elements follow a scheme of no correlation, anti-correlation, and correlation with sunspots. The anti-correlated component, covering the flux range of (2.9–32.0) × 10^{18} Mx, occupies 77.2% of total elements and 37.4% of flux on the quiet Sun. However, the stronger magnetic elements with flux larger than 4.3 × 10^{19} Mx dominate the quiet-Sun magnetic flux and follow the sunspot cycle closely.

The definitively identified anti-correlated component of the small-scale magnetic elements seems to offer an interpretation of the puzzling observations of anti-correlation variation of many types of small-scale magnetic activity with the solar cycle, e.g., the network bright points, He I 10830 Å dark points, and coronal X-ray bright points.

It is speculated that the anti-correlated small-scale magnetic elements are products of some local turbulent dynamo that is modulated to be anti-phased with the global mean-field dynamo.

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