Is It Small-scale, Weak Magnetic Activity That Effectively Heats the Upper Solar Atmosphere?

K. J. Li$^{1,2,3}$, J. C. Xu$^{1,2,3}$, and W. Feng$^4$

$^1$ Yunnan Observatories, CAS, Kunming 650011, People’s Republic of China
$^2$ Center for Astronomical Mega-Science, Chinese Academy of Sciences, Beijing 100012, People’s Republic of China
$^3$ Key Laboratory of Solar Activity, National Astronomical Observatories, CAS, Beijing 100012, People’s Republic of China
$^4$ Research Center of Analysis and Measurement, Kunming University of Science and Technology, Kunming 650093, People’s Republic of China; fengwen69@sina.cn

Received 2018 March 17; revised 2018 May 14; accepted 2018 May 17; published 2018 July 3

Abstract

Solar chromosphere and coronal heating are big questions for astrophysics. Daily measurement of 985 solar spectral irradiances (SSIs) at the spectral intervals 1–39 nm and 116–2416 nm during 2003 March 1 to 2017 October 28 are utilized to investigate phase relation with respect to daily sunspot number, the Mount Wilson sunspot Index, and the Magnetic Plage Strength Index. All the SSIs form in the abnormally heated layer; the upper photosphere, chromosphere, transition region, and corona are found to be significantly more correlated to weak magnetic activity than to strong magnetic activity, and are found to dance in step with weak magnetic activity. All the SSIs that form in the low photosphere, which indicate the “energy” leaked from the solar subsurface, are found to be more related to strong magnetic activity instead and in anti-phase with weak magnetic activity. In the upper photosphere and chromosphere, strong magnetic activity should lead SSI by about a solar rotation, which also implies that weak magnetic activity should take effect from heating there. It is thus small-scale weak magnetic activity that effectively heats the upper solar atmosphere.

Key words: Sun: activity – Sun: atmosphere – Sun: corona

Supporting material: animations

1. Introduction

For more than 70 years, researchers have puzzled over why the solar corona is much hotter than the underlying chromosphere and photosphere and how the energy from corona heating is transported upward and then dissipated (Edlen 1945; De Moortel & Browning 2015). Up to now, plenty of advances have been achieved in observational and theoretical studies for coronal heating, with particularly extraordinary progress being made in recent decades (Klimchuk 2006, 2015; Parnell & De Moortel 2012; De Moortel & Browning 2015). On one hand, recent high-resolution observations indicate that ubiquitous small-scale (a dozen arcseconds or less) isolated magnetic elements, such as network and intra-network magnetic fields and ephemeral regions, cover the solar surface like a magnetic blanket (Zirin 1988; Wilhelm et al. 2007), and small-scale magnetic activity phenomena, which are mainly related to these small-scale magnetic elements, frequently occur at the solar atmosphere and release energy there. These small-scale magnetic activity phenomena can generally be divided into the following groups: (1) spicules and macro-spicules; (2) jets, including surges, extreme ultraviolet jets, and X-ray jets; (3) bright (dark) point features, e.g., network bright points, X-ray bright points (size: $\sim 10^5$ km$^2$; lifetime: $\sim 8$ hr, and magnetic flux: $\sim 10^{20}$ Mx), microwave bright points, magnetic bright points, and He I 10830 Å dark points; (4) explosive phenomena, such as transition region explosive events and mini-filament eruptions; (5) blinkers; and (6) micro-flares and nano-flares (Golub et al. 1974; Wilhelm et al. 2007; De Pontieu et al. 2011; Zhang & Liu 2011; Tavabi & Kouchny 2014; Longcope & Tarr 2015; Schmelz & Winebarger 2015; Tavabi et al. 2015). Small-scale magnetic activity phenomena are all distributed across the full solar disk, and they are sometimes simply recorded as small-scale magnetic activity (or activities). A lot of case studies have demonstrated that these small-scale magnetic activity phenomena make a great contribution to coronal heating, and the corona is impulsively heated by them. The processes of energy build-up and release are believed to be caused by ubiquitous small-scale magnetic elements, which manifest across the solar disk as these small-scale magnetic activity phenomena (Zhang & Liu 2011; Testa et al. 2014; Longcope & Tarr 2015; Schmelz & Winebarger 2015).

On the other hand, in theoretical studies, models have been proposed to address this issue. They can be divided into two groups: magnetohydrodynamic (MHD) waves and magnetic reconnection energy releases (Alfvén 1947; Parker 1972, 1988; Cranmer 2012; Arregui 2015; Wilmot-Smith 2015). Convective flows below the solar surface and/or the emergence of magnetic fields cause a random shuffling and further twisting and braiding of the small-scale magnetic field lines. Magnetic field reconnection occurs at the braiding boundaries, creating a great deal of heat and plasma outflows, and the corona is heated by the cumulative effects of these small, localized activities (Narain & Ulmschneider 1996; Cranmer 2012; Longcope & Tarr 2015; Wilmot-Smith 2015). Observations demonstrate that both wave-heating and reconnection-heating work, but which one is the main source of coronal heating is unclear (Arregui 2015; Wilmot-Smith 2015).

Up to now, chromospheric heating has remained a bewildering mystery (Narain & Ulmschneider 1996). The standard model (VAL) of the quiet solar atmosphere shows that temperature strangely increases from the top of the photosphere to the vicinity of the coronal base, especially with a rapid increase in the transient region (Vernazza et al. 1981). So far, no compelling theories have been able to explain such a distribution of temperature (Narain & Ulmschneider 1996;
Dunin-Barkovskaya & Somov 2016). Therefore, heating is actually an unresolved issue for all layers of the upper solar atmosphere, although most attention has been paid to coronal heating.

In this study, daily solar spectral irradiances in 985 spectral bands, which form in different layers of the solar atmosphere, are utilized to investigate their (phase) relationships with solar magnetic activity indexes, leading to some statistical evidence accidentally arising that indicates small-scale weak magnetic activity heats the upper solar atmosphere.

2. Observations and Data Reduction

Solar spectral irradiances (SSIs) at the spectral intervals 1–39 nm and 116–2416 nm, which were measured by the SORCE satellite during 2003 March 1 to 2017 October 28, are available at http://lasp.colorado.edu/home/sorce/data/. SSIs are measured in 985 spectral bands, samples of which are provided here as time-series of 7 bands, as shown in Figure 1. SSI is not measured frequently, and Figure 2 shows the number of measurement days for all spectral bands for a total of 5356 days. For those SSIs whose bands are shorter than 1600 nm, the number of measurement days is almost constant, about 5000 days. For the 985 bands we study, the maximum span of a band is 1 nm, and thus wavelength ($L$) is used to replace “spectral band” in the figure, which is the middle value of a band.

Daily SSIs are used to investigate phase relations with daily sunspot numbers (SSNs). Daily SSNs (version 2) at the same time intervals can be found at http://sidc.oma.be/silso/, and are shown in Figure 3. SSN itself is a kind of count of large-scale magnetic structures, but the time-series of SSNs are usually used to reflect the temporal occurrence frequency of large-scale activity phenomena, such as, for example, flares, which are related to large-scale magnetic structures.

The Mount Wilson sunspot Index (MWSI) and the Magnetic Plage Strength Index (MPSI) are calculated at the Mount Wilson observatory through daily magnetograms (Howard et al. 1980). Also used are daily MWSIs and MPSIs during the time period 2003 March 1 to 2012 December 31, which are sourced from http://obs.astro.ucla.edu/intro.html and also shown in Figure 3. MWSI and MPSI are not observed frequently, as indicated by the fact they were seen on just 2591 of the total 3594 days. MWSIs and MPSIs themselves are a kind of count of strong magnetic fields (mainly in sunspots) across the full solar disk and that of weak magnetic fields (mainly at outside of sunspots; Howard et al. 1980; Xiang et al. 2014), correspondingly. Here, the time-series of the weak-magnetic-element index, MPSIs, are used to reflect the temporal occurrence frequency of the aforementioned small-scale magnetic activity phenomena, which are related to the weak magnetic elements, and the time-series of
the strong-magnetic-element index, MWSIs, are used to reflect the occurrence frequency of large-scale magnetic activity phenomena.

3. Data Analysis

3.1. Phase Relation between SSI and SSN

In order to study the phase relationship between daily SSI and SSN, we perform a lagged cross-correlation analysis of SSI with each of the 985 SSI time-series. First, letting two considered time-series cover the same time interval (the two can be paired with each other every day), we calculate the cross-correlation coefficient (CC) of the two time-series with no relative phase shifts. Next, one series is shifted by one day with respect to the other, and the unpaired endpoints of the two series are deleted. Then, we can obtain a new value of CC, and it is the value at a relative shift of one day. Next, the original series is shifted by 2 days with respect to the other original series, and the unpaired endpoints are deleted. Then, a new CC value can be obtained, which is the value at the relative shift of two days, and so on. If no observation record for a time-series is available on a certain day, then no measurement value for that day is considered when calculating the CC. As samples, for the seven sample SSIs shown in Figure 1, Figure 4 shows the obtained CCs as varying with relative shifts (called CC-phase lines below), where the abscissa shifts for SSN versus SSI, backward shifts are minus values, and the 985 CC-phase lines are all shown in the animation.

CC-phase lines peak around shifts of about 0 (CC0), ±27 days (CC±27) and even about ±54 days, and this is the reflection of the rotation signal for older structures. The local peak values of each of the 985 CC-phase lines around shifts of about 0 and ±27 days are given in Figure 5, which shows the local maximum when CCs around one peak are positive, or the local minimum when CCs around one “peak” (actually valley) are negative. Their corresponding 12-point running averages are also shown in the figure.

As the figure shows, peak CCs may be divided into seven parts. For Part 1, 0.5(nm) < L < 255.5(nm), CC±27 is obviously larger than CC±27, but less than CC0. As an example, these three characteristic CC values for the spectral line whose spectral band is 8–9 nm are given in Table 1. Following Li et al. (2002), we test the statistical significance for the difference in these CCs by means of the Fisher translation method (Fisher 1915), which is given in the table. As the table shows, CC±27 is statistically significantly larger than CC±27, and this implies that there should be a phase difference between SSN and the long-term variation of the SSI series, which prefers the phase leading of SSN to the lagging. CC0 is statistically significantly larger than CC±27, implying that SSN should possibly lead by about a solar rotation, but such a leading is of statistical insignificance. For Part 2, 256.5(nm) < L < 288.5(nm), CC±27 is obviously significantly larger than CC±27 (please see Table 1), and even larger than CC0. For Parts 1 and 2, CC-phase lines convexly peak around CC0. For Part 3, 289.5(nm) < L < 291.5(nm), the CC±27 that is of statistical significance is larger than the CC0 that is statistically insignificant; however, CC±27 cannot be significantly larger than CC0. From this part on, CC-phase lines start to be concave around CC0. For Part 4, 292.5 (nm) < L < 802.42(nm), the CC±27 that is of statistical significance is larger than the CC0 that is statistically insignificant; however, CC±27 cannot be significantly larger than CC0. Both CC±27 and CC0 are positive values of statistical significance. For Part 5, 806.05(nm) < L < 876.5(nm), both CC0 and CC±27 change from positive values of statistical insignificance to negative values of statistical insignificance. For Part 6, 880.71(nm) < L < 1598.95(nm), CC0 is a negative value of statistical significance. For Part 7, 1601.18 (nm) < L < 2412.34(nm), both CC±27 and CC0 disorderly vary with wavelength, and this part is no longer taken into account below. For one of the seven parts, one spectral line is chosen as a sample, which is shown in Figure 1, and its three
characteristic CCs (CC$_0$ and CC$_{+27}$) and statistical significance tests for their difference are given in Table 1. Based on Table 1, the aforementioned statistical significance is thus given if the probability is larger than 95%.

Generally, CC$_{+27}$ is significantly larger than CC$_{-27}$ for the SSIs whose wavelengths are shorter than ~800 nm. Furthermore, CC$_{+27}$ is even significantly larger than CC$_0$ for the SSIs whose wavelengths are shorter than ~800 nm but longer than ~300 nm, implying that SSNs should lead these SSIs by about a solar rotation. Strong magnetic fields in sunspot regions generally become weak magnetic fields after a solar rotation, thus this phase lead means that the SSI should be more related to weak magnetic field activity than strong magnetic field activity.

### 3.2. Phase Relation between SSIs and MWSIs and MPSIs

Similarly, we perform a lagged cross-correlation analysis of the 985 SSI time-series with MPSIs and MWSIs. As samples, for the first six sample SSIs, Figure 6 shows the obtained CCs as varying with relative phase shifts, where the abscessa shifts for MPSI (or MWSI) versus SSI, and backward shifts are given minus values. CC-phase lines peak around shifts of about +27 days, displaying the solar rotation signal.

Table 2 shows the CC$_0$s and CC$_{+27}$s of the first six sampled lines. CC$_0$ is even up to 0.9366 for the first sample line, indicating that the corresponding SSI should be closely related to weak magnetic field activity. Probabilities are given in Table 2, and accordingly the statistical significance can be found if the probability is larger than 95%. The CC$_0$ of MPSI versus SSI is significantly larger than the CC$_0$ of MWSI versus SSI for the SSIs whose wavelengths are shorter than ~800 nm, implying that these SSIs should be more related to weak magnetic field activity than strong magnetic field activity.

Similarly, the local peak values of a CC-phase line around shifts of about 0 and ±27 days are given in Figure 7 for SSI versus MPSI and in Figure 8 for SSI versus MWSI, and their 12-point averages are also given in the corresponding figures. Statistical significance tests for differences in three characteristic CCs are shown in Table 2. The peak CCs in Figures 7 and 8 can be divided into seven parts, as done in Figure 5.

We choose SSNs that were recorded on the same days that MPSIs were observed (the two are simultaneously observed), which are here called the chosen SSN, and then perform a lagged cross-correlation analysis of the chosen SSN using the time-series from the 985 SSIs. Similarly, Figure 9 shows the local peak values of a CC-phase line around shifts of about 0 and ±27 days. As Figures 7–9 show, generally CC$_{+27}$ is significantly larger than CC$_{-27}$ for SSIs whose wavelengths are shorter than ~800 nm, implying that weak magnetic activity should clearly influence SSI after a solar rotation. The CC$_{+27}$ of both SSNs and MWSIs with respect to SSIs are even significantly larger than the corresponding CC$_0$ for SSIs whose wavelengths are shorter than ~800 nm but longer than ~300 nm, implying that strong magnetic field activity indexes (SSNs and MWSIs) should lead SSIs by a rotation. Three CC$_0$ lines shown in Figures 7–9 are put together in Figure 10, which clearly shows that SSIs whose wavelengths are shorter than ~800 nm (Parts 1 to 4) should be much more related to MPSI than to MWSI, and that SSI whose wavelengths are longer than ~800 nm and shorter than ~1600 (Part 6) should generally be more related to MWSI than to MPSI. The CC$_0$ of MPSIs with SSIs at X-rays and the far-ultraviolet are obviously larger than those at the visible-light band, implying that the relationship between small-scale weak magnetic activity and SSI is much more intimate at X-rays and the far-ultraviolet than that at visible-light band. The CC$_0$ for SSIs versus the chosen SSNs is located between CC$_0$ for SSIs versus MPSIs and CC$_0$ for SSIs versus MWSIs, implying that the magnetic fields of sunspots that are all counted as SSN should be counted partly into MWSI and partly into MPSI.

Comparing Figures 5 and 9 shows that missing data should change the values of CC, but the relative trend of CC$_0$ and CC$_{+27}$ still exists, and is slightly influential.

### Table 1

| Spectral band | CC$_0$ | CC$_{+27}$ | CC$_{-27}$ | Probability (CC$_{+27}$ vs. CC$_0$) | Probability (CC$_{+27}$ vs. CC$_{-27}$) |
|---------------|--------|------------|-----------|-------------------------------------|----------------------------------------|
| 8–9 nm        | 0.8664 | 0.7827     | 0.7311    | >99.9%                              | >99.9%                                 |
| 266–267 nm    | 0.5801 | 0.6195     | 0.5583    | >99.9%                              | ...                                    |
| 289–290 nm    | 0.0811 | 0.1144     | 0.0882    | 76%                                 | ...                                    |
| 431.47 nm     | 0.3966 | 0.5061     | 0.4377    | >99.9%                              | ...                                    |
| 843.96 nm     | 0.020  | 0.1016     | 0.0438    | 99.5%                               | ...                                    |
| 1040.57 nm    | −0.2434| −0.2021    | −0.2185   | 88%                                 | ...                                    |
| 1616.86 nm    | −0.0393| −0.0518    | −0.0325   | ...                                 | ...                                    |
4. Conclusions and Discussion

X-rays and far-ultraviolet spectra form in the transition region and corona, middle and near-ultraviolet spectra form over or in the top chromosphere, SSIs at visible-light wavelengths (400 ∼ 800 nm) form in the chromosphere or in the upper photosphere, and SSIs at infrared wavelengths (900 ∼ 1600 nm) mainly form in the low photosphere (Vernazza et al. 1981; Ding & Fang 1989; Harder et al. 2009; Meftah et al. 2018). Therefore, Figures 5 and 10 indicate that in the low photosphere SSI is negatively correlated with SSN and more related to strong magnetic activity than to weak magnetic activity, but in and above the top photosphere, SSI is positively correlated with SSN, and significantly more related to weak magnetic activity than to strong magnetic activity. Correspondingly, as the VAL atmosphere model (Vernazza et al. 1981) shows, temperature decreases toward the outside in the low photosphere, but abnormally increases from the top photosphere up toward the corona (the abnormally heated layer). Therefore, the layer at which temperature decreases is found to correspond to the layer at which SSI is in anti-phase with SSN and more related to strong magnetic activity than to weak magnetic activity, and the layer at which temperature abnormally increases is found to be the layer at which SSI is

| Spectral band | SSI versus MPSI | SSI versus MWSI | Probability for these two CCs |
|---------------|-----------------|-----------------|-----------------------------|
| 8–9 nm        | 0.9366          | 0.7289          | >99.9%                      |
| 266–267 nm    | 0.7381          | 0.4478          | >99.9%                      |
| 289–290 nm    | 0.2759          | 0.1677          | >99.9%                      |
| 431.47 nm     | 0.5151          | 0.0820          | >99.9%                      |
| 843.96 nm     | 0.1805          | −0.1981         | >99.9%                      |
| 1040.57 nm    | −0.5324         | −0.6541         | >99.9%                      |

| CC0 | CC27 | Probability |
|-----|------|-------------|
| 0.9366 | 0.8660 | >99.9%     |
| 0.7289 | 0.6166 | >99.9%     |
| 0.4478 | 0.5230 | >99.9%     |
| 0.1677 | 0.2512 | >99.9%     |
| 0.0820 | 0.4317 | >99.9%     |
| −0.1981 | 0.1219 | >99.9%     |
| −0.6541 | −0.3145 | >99.9%     |
| 0.5151 | 0.6184 | >99.9%     |
| 0.0820 | 0.4317 | >99.9%     |
| 0.1805 | 0.2359 | 85%        |
| −0.5324 | −0.4600 | 98%        |

**Table 2**
Statistical Significance for Differences in the Characteristic CCs of SSIs vs. MPSIs and MWSIs

**Figure 7.** Local peak values of a cross-correlation coefficient line (MPSI vs. SSI) around shifts of about 0 (black dots), −27 (yellow dots), and 27 days (red dots). The solid lines are the corresponding 12-point smoothing averages.

**Figure 8.** Local peak values of a cross-correlation coefficient line (MWSI vs. SSI) around shifts of about 0 (black dots), −27 (yellow dots), and 27 days (red dots). The solid lines are the corresponding 12-point smoothing averages.

**Figure 9.** Local peak values of a cross-correlation coefficient line (the chosen SSN vs. SSI) around shifts of about 0 (black dots), −27 (yellow dots), and 27 days (red dots). The solid lines are the corresponding 12-point smoothing averages.
phase with SSN and more related to weak magnetic activity. The abnormally heated layer accurately corresponds to the layer where weak field activity has a more obvious impact on SSI, and outside that layer, strong magnetic activity has the greater impact.

Long-term variation of “energy” across the entire abnormally heated layer, from the top photosphere, to the chromosphere, to the corona, dances in step with weak magnetic activity. The long-term fluctuation of the SSI that forms at the bottom of the photosphere, which reflects long-term variation of “energy” leaked from the solar interior, completely differs from that of the SSI that forms at the abnormally heated layer. Therefore, it should naturally be weak magnetic activity that causes the abnormal temperature distribution. At the base of the abnormally heated layer, namely in the top photosphere and chromosphere, strong magnetic activity is found to lead SSI by about one solar rotation. Solar strong magnetic structures (sunspots) are first observed when they appear on the solar disk, and their evolutionary components should be observed after rotating to appear again on the solar visible disk as disintegrated components (small-scale weak magnetic elements). Because sunspots are darker than the background photosphere and chromosphere and become weak magnetic elements after a solar rotation, the $CC_{27}$ of both SSNs and MWSIs (strong magnetic field indexes) versus SSIs is obviously larger than the corresponding $CC_0$ in the top photosphere and chromosphere, indicating that strong magnetic activity should lead SSIs by about a solar rotation, and such a phase lead also implies weak magnetic activity heating. These results are illustrated in Figure 11. Furthermore, more reconnection events of small-scale magnetic activity are observed in higher atmosphere layers, the transition region and corona, and thus temperatures are higher in the higher layers. Correspondingly, the relation for small-scale magnetic activity (MPSIs) for the SSIs at short wavelengths, X-rays and the far-ultraviolet, formed at higher layers, is also closer than that of MPSIs, with the SSIs at long wavelengths (the visible-light band) forming in the top photosphere and chromosphere, and the time-series of the SSIs at the short wavelengths more violently fluctuating (see the SSI time-series given in Figure 1 and its animation), namely, the SSIs at the short wavelengths more obviously respond to weak magnetic activity. All findings point toward heating of the chromosphere, transition region, and corona occurring due to weak magnetic activity. Li et al. (2012) found that total solar irradiance is more closely related to network magnetic elements than strong magnetic fluxes of sunspot groups, in agreement with the above conclusion.

Ubiquitous rapidly rotating magnetic structures (tornadoes) on small scales are observed to channel energy from the photosphere upward into the high solar atmosphere (Zhang & Liu 2011; Wedemeyer-Bohm et al. 2012). High-resolution observations displayed hot plasma flowing from the photosphere upward to the corona (heating there) along fine loops which originate in the intergranular lanes, and this is observational evidence for small-scale magnetic activity heating in the high atmosphere (Ji et al. 2012). Recently, through analyzing observational data of the quiet Sun by the Interface Region Imaging Spectrograph, Tavabi (2018) found a strong relationship among the network bright points at all layers of the solar atmosphere and suggested that magnetic field concentrations in the network rosettes should helpfully couple between the inner and outer solar atmosphere. Thus, our statistical result is supported by observations, and synchronously heating of all the layers of the high solar atmosphere (from the upper photosphere to the corona) is feasible.

Although wave-heating is an important mechanism for the coronal heating (De Pontieu et al. 2007; Tavabi et al. 2011; Arregui 2015; Wilmot-Smith 2015), the heating of waves emerging from the solar interior should seemingly not be the main heating mechanism (source) of the high solar atmosphere, that is, the magnetic reconnection mechanism seems more important than the wave-heating mechanism for the following...
reasons. (1) The physical situation is very different between different layers in the upper photosphere, chromosphere, transition region, and corona, thus synchronously heating these layers seems unlikely through wave dissipation. (2) It is hard to explain that those SSIs that form at these layers are all in phase with SSN and more related to weak magnetic activity (MPSI), and especially hard to explain the phase lead of strong magnetic activity with respect to SSI by wave-heating. Of course, the contributions of waves to heating the high solar atmosphere have been observed. After excluding the wave-heating from the main heating mechanism, the remaining reconnection-heating mechanism can indeed explain the strong relation between those SSIs with weak magnetic activity and thus the phase lead.

As noted in the first section, high-resolution observations suggest coronal heating is caused by small-scale weak magnetic activity. Particularly, magnetic reconnection was found to occur on a very small spatial scale throughout the solar chromosphere by Shibata et al. (2007), and they believed that the heating of the chromosphere and corona should be connected to small-scale ubiquitous reconnection. Also, ubiquitous small-scale spicules/jets have been observed to supply the mass accelerated upward into the corona (De Pontieu et al. 2011). The corona has been observed to be heated by the interaction between emerging regions and the surrounding quiet magnetic fields of small-scale reconnections (Zhang et al. 2017).

Up to now, high-resolution observations have provided evidence for weak magnetic activity heating high solar atmosphere just through local heating channel, but how the heated atmosphere is globally related to weak magnetic activity (ubiquitous small-scale active events) has not previously been investigated, and it is hard to address this issue. Here, we do not yet directly answer this question, but a comparison of the temporal variations (SSIs) of the heated atmosphere is carried out with weak magnetic activity (events), which is represented by weak magnetic index (MPSIs). Our findings consider the final effects of the global heating, and exclude other possible mechanisms of heating. Our statistical evidence is compelling, and is even stronger when observational evidence is also considered.

Sunspots present themselves as dark constructs in the photosphere and low and middle chromosphere, but are bright in the top chromosphere and transition region (Ding & Fang 1989). Therefore, the aforementioned CC-phase lines of SSNs (or MWSIs) versus SSIs convexly peak around CC0 for SSIs whose wavelengths are shorter than about 290 nm (the appearance of sunspots on the visible disk as bright constructs should lead to increasing SSI), but are concave for SSIs whose wavelengths are longer than about 300 nm (sunspots present as dark constructs decrease SSI). Some of the SSIs at the infrared wavelengths, 1600 ~ 2400 nm (Part 7), may form in the low photosphere, some form in or over the top photosphere, and some even possibly come from both; thus some SSIs at this spectral interval are in phase with SSN, but some are not. Therefore, SSIs at this spectral interval disorderly vary with wavelength.

SSIs and SSN fluctuate strongly in amplitude, and smoothed data should be expected to statistically present a higher CC than the original data. However, SSIs, MPSIs, and MWSIs are seriously discontinuous, and this could be an obstacle for future studies. In cases where the fluctuation components of high frequencies are excluded, the relationships between the long-term variations of SSIs and SSNs, MPSIs, and MWSIs, are believed to be more robust than those in cases where the fluctuation components of high frequencies are included. Therefore, the obtained physical conclusions are more reliable than those when short-term variations are eliminated.

Finally, it should be emphasized that some magnetic indexes (SSN, Mg II index, and so on) are used as “proxy” indexes in the research field of SSI/TSI (total solar irradiance) reconstruction (Lean 2000; Frohlich 2006; Steiner 2007; Fontenla et al. 2011; Ermolli et al. 2013; Yeo et al. 2014; Dudok de Wit et al. 2018 and references therein), and stand in for magnetic structures on the solar disk, but here the time-series of magnetic indexes are used to reflect the temporal occurrence frequency of magnetic activity phenomena (events), which are related to the corresponding magnetic structures of the indexes. The temporal variation of the heated high atmosphere is reflected by the SSIs that form there, and the temporal variation of the occurrence frequency of small-scale weak magnetic activity phenomena is reflected here by MPSIs. On the one hand, the special (phase) relation of SSIs and MPSIs, which clearly differs from that of SSIs and MWSIs/SSNs, which removes the main wave-heating mechanism, obscures the major contributions of strong magnetic activity to heating the high atmosphere. On the other hand, the primary reason why those SSIs forming at high atmosphere layers vary in the long-term is the heating of small-scale weak magnetic activity phenomena.

The authors thank the anonymous referee for carefully reading the manuscript and providing constructive comments that improved the original version of the manuscript. We thank Profs. Jingxiu Wang and Mingde Ding for helpful discussion and useful suggestions. The SORCE Solar Spectral Irradiance (SSI) composite data product is constructed using measurements from the XPS, SOLSTICE, and SIM instruments, which are combined into merged daily solar spectra over the spectral intervals (1–39 nm and 116–2416 nm). Sunspot data come from the World Data Center SILSO, Royal Observatory of Belgium, Brussels. This study includes data (MPSIs and MWSIs) from the synoptic program at the150-Foot Solar Tower of the Mt. Wilson Observatory. The Mt. Wilson 150-Foot Solar Tower is operated by UCLA, with funding from NASA, ONR, and NSF, under agreement with the Mt. Wilson Institute. All data used here were obtained from the websites of these institutions. The authors would like to express their deep thanks to the staffs of these websites. This work is supported by the National Natural Science Foundation of China (11573065 and 11633008) and the Chinese Academy of Sciences.

**References**

Alfven, H. 1947, MNRAS, 107, 211

Arregui, I. 2015, RSPTA, 373, 20140261

Cranmer, S. R. 2012, SSRv, 172, 145

De Moortel, I., & Browning, P. 2015, RSPTA, 373, 20140269

De Pontieu, B., McIntosh, S. W., Carlsson, M., et al. 2007, Sci, 318, 1574

De Pontieu, B., McIntosh, S. W., Carlsson, M., et al. 2011, Sci, 331, 55

Ding, M. D., & Fang, C. 1989, A&A, 225, 204

Dudok de Wit, T., Kopp, G., Shapiro, A., Witzke, V., & Kretzschmar, M. 2018, ApJ, 853, 197

Dunin-Barkovskaya, O. V., & Somov, B. V. 2016, AstL, 42, 825

Edlen, B. 1945, MNRAS, 105, 323

Ermolli, I., Matthes, K., Dudok de Wit, T., et al. 2013, ACP, 13, 3945

Fisher, R. A. 1915, Bionetrika, 10, 507
Fontenla, J. M., Harder, J., Livingston, W., Snow, M., & Woods, T. 2011, JGRD, 116, D20108
Frohlich, C. 2006, SSRv, 125, 53
Golub, L., Krieger, A. S., Silk, J. K., Timothy, A. F., & Vaiana, G. S. 1974, ApJL, 189, L93
Harder, J. M., Fontenla, J. M., Pilewskie, P., Richard, E. C., & Woods, T. N. 2009, GeoRL, 36, L07801
Howard, R., Boyden, J. E., & LaBonte, B. J. 1980, SoPh, 66, 167
Ji, H. S., Cao, W. D., & Goode, P. R. 2012, ApJL, 750, L25
Klimchuk, J. A. 2006, SoPh, 234, 41
Klimchuk, J. A. 2015, RSPTA, 373, 20140256
Lean, J. L. 2000, SSRv, 94, 30
Li, K. J., Feng, W., Xu, J. C., et al. 2012, ApJ, 747, 135
Li, K. J., Irie, M., Wang, J. X., et al. 2002, PASJ, 54, 787
Longcope, D. W., & Tarr, L. A. 2015, RSPTA, 373, 20140263
Metfield, M., Dame, L., Bolsee, D., et al. 2018, A&A, 611, A1
Narasimhan, U., & Ulmschneider, P. 1996, SSRv, 75, 453
Parker, E. N. 1972, ApJ, 174, 499
Parker, E. N. 1988, ApJL, 330, 474
Parnell, C. E., & De Moortel, I. 2012, RSPTA, 370, 3217
Schmelz, J. T., & Winebarger, A. R. 2015, RSPTA, 373, 20140257
Shibata, K., Nakamura, T., Matsumoto, T., et al. 2007, Sci, 318, 1591
Steiner, O. 2007, in AIP Conf. Proc. 919 (Melville, NY: AIP), 74
Tavabi, E. 2018, MNRA, 476, 868
Tavabi, E., & Koutchmy, S. 2014, ApSS, 352, 7
Tavabi, E., Koutchmy, S., & Ajabshirizadeh, A. 2011, NewA, 16, 296
Tavabi, E., Koutchmy, S., & Golub, L. 2015, SoPh, 290, 2871
Testa, P., de Pontieu, B., Allred, J., et al. 2014, Sci, 346, 1255724
Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, ApJS, 45, 635
Wedemeyer-Bohm, S., Scullion, E., Steiner, O., et al. 2012, Natur, 486, 505
Wilhelm, K., Marsch, E., Dwivedi, B. N., & Feldman, U. 2007, SSRv, 133, 103
Wilmoth-Smith, A. L. 2015, RSPTA, 373, 20140265
Xiang, N. B., Qu, Z. N., & Zhai, Q. 2014, AI, 148, 12
Yeo, K. L., Krivova, N. A., & Solanki, S. K. 2014, SSRv, 186, 137
Zhang, J., & Liu, Y. 2011, ApJL, 741, L7
Zhang, J., Zhang, B., Li, T., et al. 2017, ApJL, 799, L27
Zirin, H. 1988, Astrophysics of the Sun (Cambridge: Cambridge Univ. Press)