Behavior of Some Narrow Band of Solar Spectral Irradiance during the Solar Cycles 21

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Abstract. The study of variations of the spectral irradiance is presented. Observations recorded by the Solar Radiation and Climate Experiment (SORCE) mission supported by the Laboratory for Atmospheric and Space Physics (LASP) have been used. We have investigated a narrow band of solar spectral irradiance in the far ultraviolet (FUV) and ultraviolet (UV) ranges for period 1981-2008. The investigation results of correlation relationship between solar spectral irradiance variations and solar sunspot number are given for the studied period. The investigated data cover the decreasing phases of the solar activity cycles 21, 22 and 23 and increasing phases of the solar cycles 22 and 23. Using the software developed by us we have studied emission variations of discrete solar spectral lines extracted from the NASA data archives. We have revealed a peculiar behavior of intensities of some solar ultraviolet spectral lines originated in the solar chromosphere during unusually prolonged minimum between solar activity cycles 23 and 24. The variations of these intensities do not agree equally well with the total solar radiation and sunspot number (SN) variations during descending phase of the solar activity 23, that seems unusual for the solar ultraviolet spectral range. It is known that anti-correlation between appropriate helio-seismic frequencies and activity proxies during the minimum period between the solar activity cycles 23-24 was also revealed according the helio-seismic data obtained by the Global Oscillation Network Group (GONG) and the Michelson Doppler Imager (MDI) onboard Solar and Heliospheric Observatory (SOHO) spacecraft. Taking into account helio-seismic data variations, the revealed negative correlations between sunspot number and some solar spectral narrow bands of UV emission (289.5 nm, 300.5 nm) can be explained by the close connection of these emissions with the super-granules and plages. So the existence of the negative correlation can be explained by the reason that these objects are sensitive to the solar magnetic fields.

Keywords: Solar spectral irradiance, Solar activity cycle, correlation

Introduction

Variations of the solar spectral irradiance (SSI), in particular variations of the ultraviolet (UV) radiation play a significant role in the way the Sun influences the Earth's climate system (Bouwer et al., 1990). It is considered that the solar extreme ultraviolet and ultraviolet radiation (EUV&UV) dominates in processes of solar-terrestrial connection. Solar radiation below 300 nm is almost completely absorbed in the upper atmosphere, stratosphere and changes the chemical composition and dynamical parameters of those layers and causes variations of the ozone concentration (Brasseur and Solomon, 1984; Rees, 1989; Lean, 1991; Haigh, 1996). However, the contribution of UV and EUV radiation in the total solar irradiance (TSI) is rather small, only a few percent (Kane, 2005).

The solar cycle 23 is the best observed solar cycle at present, with obtained data from SOHO/ VIRGO mission starting in 1996, ACRIMSat/ACRIM3 missions starting in 2000, and SORCE/TIM mission starting in 2003. It is considered that the solar cycle 23 (years 1996-2008, with maximum of sunspot number in 2000) has got its own peculiarities and can be characterized as an anomalous one (de Toma et al., 2004). The cycle is weaker than its preceding cycles 21 and 22 almost in all of the solar indices – magnetic flux, sunspot area, faculae area, Mg II index, and 10.7 cm radio flux (but not in TSI). The burst of activity in December 2006 was very exceptional and untypical for a very late declining phase. The minimum phase of the solar cycle 23 has been unusually long, with nearly 700 days without sunspots. Such a number of spotless days have not been observed since 1933. The entire duration of solar cycle 23 was longer than duration of previous cycles 21 and 22. Besides, the solar wind was reported to be in a uniquely low energy state since space measurements begun nearly 40 years ago (Fisk and Zhao, 2009). Many efforts are underway in order to understand what are the main mechanisms responsible for such a prolonged period with minimal solar activity as well as for other untypical events characterized the solar activity cycle 23. The peculiarities of the solar cycle 23 caused us to investigate solar spectral irradiance variations for the purpose to find out possible special features of irradiance variations for the solar cycle 23. Based on the consideration of abnormality of the solar cycle 23 we decided to investigate how well the irradiance variability of separate narrow spectral bands coincides with the solar activity index - international sunspot number (ISN) and total solar irradiance (TSI) for different solar cycles (21-23), to reveal possible anomalous behavior in SSI variations for the years 2003-2008 and estimate existing correlations quantitatively.

The data processing includes: a) extracting and compiling of selected quantities, b) creation of the homogeneous local dataset of formatted data suitable for following processing, c) statistical processing of investigated data (regressive analysis, correlation analysis).

Data description

The study in this paper is based on more than twenty years of solar total and spectral irradiance measurements obtained by space experiments.

Solar spectral irradiance data were extracted from the NASA data archives provided interactive and direct access to a comprehensive set of solar spectral irradiance measurements from the soft X-ray (XUV) at 0.1 nm up to the near infrared (NIR) at 2400 nm, as well as the measurements of total solar irradiance (TSI). The data contain hourly and daily measurements and are merged into ASCII text-files making data convenient for following processing.

We have investigated the SSI data in the range of 120-300 nm for the solar cycles 21, 22 and 23, based on spectral time series of solar far ultraviolet (FUV) and UV irradiance measurements obtained by the Solar Mesosphere Explorer (SME, 1981-1989, available wavelength range 115.5-302.5 nm), Upper Atmosphere Research Satellite (UARS, 1991-2001, available wavelength range 119.5– 425.5 nm) and Solar Radiation and Climate Experiment (SORCE, 2003-2009, available wavelength range 116.5–1598.95 nm) experiments. The data of solar spectral irradiance analyzed in this paper were been extracted from the following datacenters: National Space Science Data Center (NSSDC), Goddard Distributed Active Archive Centre (GDAAC) and LASP Interactive Solar Irradiance Datacenter (LISIRD) that serve as the archives for NASA space science mission data. The international sunspot number data and total solar irradiance data are used as well. ISN data are obtained from the Solar Influences Data Analysis Center (SIDC), World Data Center for the Sunspot Index, at the Royal Observatory of Belgium. TSI data products are formulated using measurements made by the Active Cavity Radiometer Irradiance Monitor (ACRIM) experiments providing ongoing calibrated high precision values.

We have developed software for extracting and processing of narrow bands spectral irradiance data.

To compare the solar spectral irradiance variations of the selected narrow bands with TSI and ISN variations we have chosen the following wavelengths from the solar spectral irradiance database: 121.5 nm, 200.5 nm, 289.5 nm, 300.5 nm, using the software developed on the base of the latest version of MATLAB.

Linear data interpolation inside the missing interval was used in the case when data were missed. We have interpolated daily values of data indices to get continuous and spectrally resolved measurements of the irradiance and more obvious trends of time series. In the case when there were several data for a given day their values were averaged. As a result, the daily sequences of selected values were obtained.

List of selected data used in the present analysis is given in the Table 1. In the Table 1 space flight experiments and data archives are indicated as well for selected data according to the increasing and decreasing phases of the solar activity cycles 21-23.

Table 1: List of the data used in the present analysis.

Data	Origin Region	Spaceflight experiments and data archives				
		1981-1986	1987-1989	1992-1996	1997-1999	2003-2008
121.5 nm emission	Transition Region of the Sun	SME (NSSDC)	SME (NSSDC)	UARS (GDAAC)	UARS (GDAAC)	SORCE (LISIRD)
200.5 nm emission	Chromosph.	SME (NSSDC)	SME (NSSDC)	UARS (GDAAC)	UARS (GDAAC)	SORCE (LISIRD)
289.5 nm emission	Chromosph.	SME (NSSDC)	SME (NSSDC)	UARS (GDAAC)	UARS (GDAAC)	SORCE (LISIRD)
300.5 nm emission	Chromosph.	SME (NSSDC)	SME (NSSDC)	UARS (GDAAC)	UARS (GDAAC)	SORCE (LISIRD)
ISN	Sun Surface	SIDC	SIDC	SIDC	SIDC	SIDC
TSI	Sun Surface	ACRIM1	ACRIM1 Nimbus7/ERB ACRIM2	ACRIM2	ACRIM2	ACRIM3

Data analysis and results

To compare the solar spectral irradiance variations of the selected narrow bands with TSI and ISN variations we have chosen the following wavelengths from the solar spectral irradiance database: 121.5 nm, 200.5 nm, 289.5 nm, 300.5 nm belonged to the solar UV range of the solar spectrum. 121.5 nm (Lyman-α) emission is originated in transition region of the Sun, 200.5 nm, 289.5 nm and 300.5 nm lines emission is originated in the solar chromosphere. Selected ASCII data have been reduced using the latest version of the software MATLAB.

Statistical processing of selected data includes following steps:

interpolation of missing data;

primary processing of selected data (timed average, smoothed average);

regression analysis of selected data to reveal linear fits;

determination and estimation of correlation coefficients for time series of selected data.

Variations of daily values of selected narrow band of SSI for the solar cycles 21, 22 and 23 are presented on Figures 1-5. For more evidence we have located selected data time series in one figure using standardized values.

Data were standardized by the equation:

$$y_s = \frac{y_i - y}{\sigma_y} \quad (1)$$

where, y_s are standardized values, y_i - daily average meanings of data, $\bar{y}$ - time average meaning of selected data, σ_y – standard deviation of selected data.

As we can see from the Figures 1-5, variability of emission of some solar spectral lines (121.5 nm, 200.5 nm) clearly repeats the main trends of sunspot number and TSI for solar activity cycles. However, some of the spectral lines emission indicates opposite behavior (289.5 nm, 300.5 nm). We found that anti-correlation takes place between intensities of some narrow band of solar spectrum and ISN and TSI for the decreasing phase of the cycle 23.

Figure 5 obviously indicates a peculiar behavior of 289.5 nm and 300.5 nm spectral lines intensity variations.

To explore correlation between solar spectral intensity variations and sunspot number during solar activity phases we investigated relationship between these parameters using 10-day averaged meanings and calculated correlation coefficients (r) between intensity variations of separate spectral irradiances, TSI and SN we used an equation:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{(\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2)^{1/2}} \quad (2)$$

where x_i and y_i correspond to the two different time series of running averaged values selected from SSI, TSI and SN data, i indicates a number of measurement, $\bar{x}$ and $\bar{y}$ are timed averages of selected data. Calculated meanings of correlation coefficients are given in the table 2. Confidence levels for the calculated coefficients are more than 95%.

We computed linear fits for each of selected spectral intensities as well. Obtained results graphically are shown on Figures 6-9.

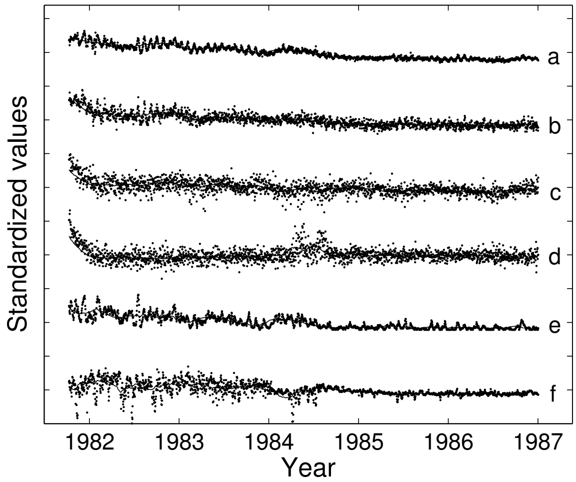

Figure 1: Variations of standardized daily values of selected narrow band intensities 121.5 nm (a), 200.5 nm (b), 289.5 nm (c), 300.5 nm (d), sunspot number (e) and solar total irradiance (f). Daily meanings of amplitudes of irradiance intensities and sunspot numbers are standardized to the corresponding standard deviations. Standardized values are shown as data points. Solid lines correspond to smoothed data creating by moving average made on 60 points basis. The horizontal axis corresponds to the period 8 October 1981 – 31 December 1986

We have calculated and estimated A and B coefficients of the linear regression $y = Ax + B$ for relationships between selected SSI and ISN by equations 3-6:

$$A = \frac{(\sum x_i^2)(\sum y_i) - (\sum x_i)(\sum x_i y_i)}{\Delta} \quad (3)$$

$$B = \frac{N(\sum x_i y_i) - (\sum x_i)(y_i)}{\Delta} \quad (4)$$

$$\sigma_A^2 = \frac{\sigma_y^2 \sum x_i^2}{\Delta} \quad (5), \qquad \sigma_B^2 = \frac{N\sigma_y^2 \sum x_i}{\Delta} \quad (6)$$

where x_i corresponds to 10-day averaged values selected from SSI data and y_i corresponds to ISN data, N is a total number of data, i indicates a number of measurements, Δ and σ_y are calculated by equations 7-8:

$$\Delta = N \sum x_i - (\sum x_i)^2 \quad (7)$$

$$\sigma_y^2 = \frac{1}{N-2} \sum (y_i - A - Bx_i)^2 \quad (8)$$

Obtained results are presented in the Table 3

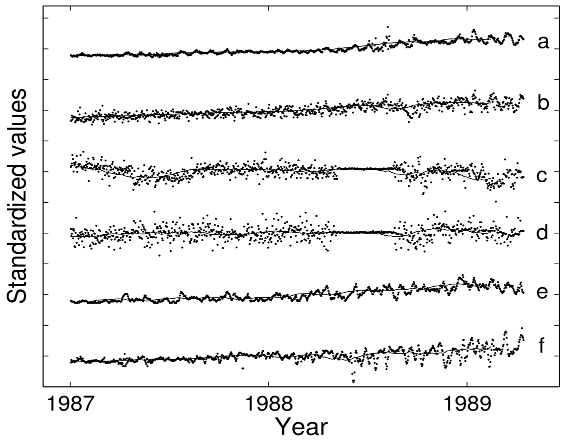

Figure 2: The same as in Figure 1 for the period 1 January 1987 – 13 May 1989

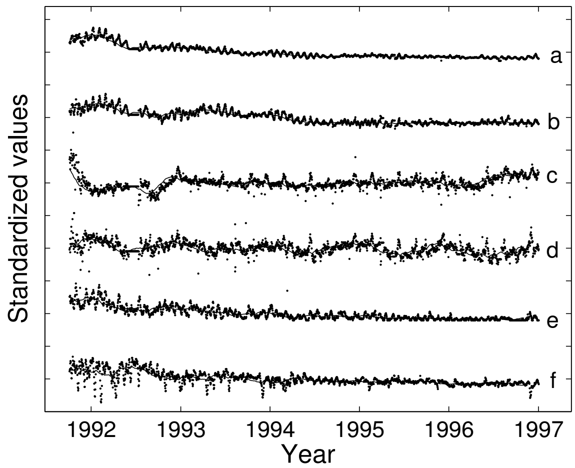

Figure 3. The same as in Figure 1 for the period 3 October 1991 – 31 December 1996

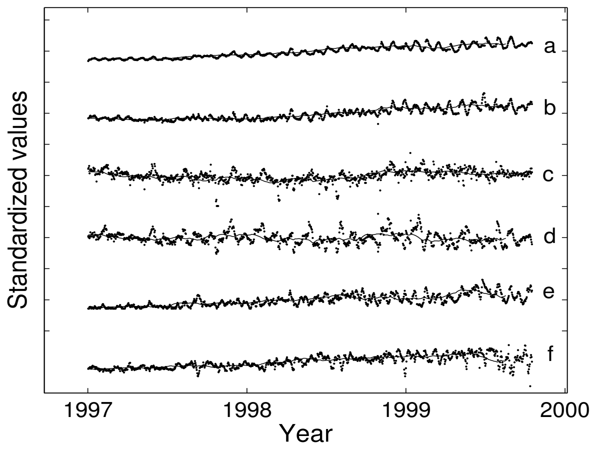

Figure 4. The same as in Figure 1 for the period 1 January 1997 – 15 October 1999

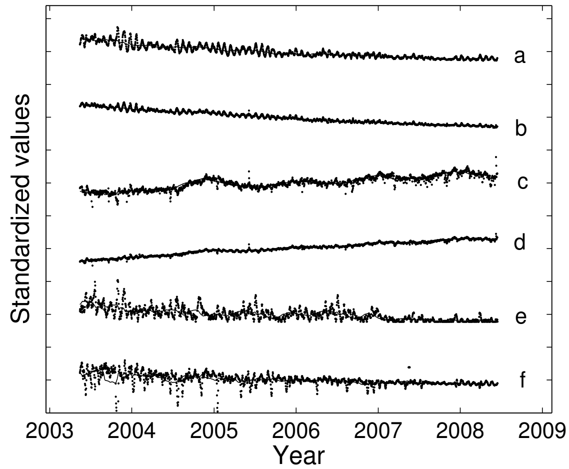

Figure 5. The same as in Figure 1 for the period 14 May 2003 – 14 June 2008

Discussion

Solar FUV and UV irradiance originates mostly in the solar photosphere and chromosphere. Temporal variability of solar UV emission modulates global climate processes of the Earth. Investigation of solar UV irradiance variability gives a good possibility for better understanding of physical processes existing on the Sun. Since the first space measurements of solar irradiance in the late seventies, the Sun has been constantly monitored with a precision high enough to detect even variations of the order of 0.01% (Wilson and Hudson, 1988; Fröhlich and Lean, 1988).

It is considered that the solar irradiance in the EUV and UV can be decomposed into different contributions, which makes the modeling of the spectral variability relatively easier (Vernazza and Reeves, 1978; Woods et al., 2000; Warren, 2005)

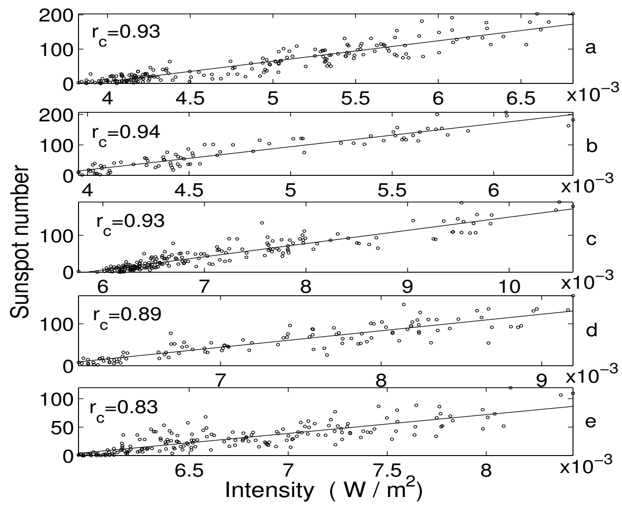

Figure 6: Linear fits for relationships between ISN and 121.5 nm spectral line emission intensity for solar activity cycles 21-23. a) – decreasing phase of the solar activity cycle 21, b) – increasing phase of the solar activity cycle 22, c) – decreasing phase of the solar activity cycle 22, d) – increasing phase of the solar activity cycle 23, e) – decreasing phase of the solar activity cycle 23. 10-day averages are used. Solid lines correspond to linear fits

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computed by the least-squares method. Corresponding correlation coefficients are indicated

Table 2: Correlation coefficients are given between intensity variations of the selected narrow bands of solar spectrum and ISN (1981-2008) for the solar activity cycles 21, 22 and 23. Data were smoothed by timed average made on 10 points basis.

Year / Wavelength	1981-1986	1987-1989	1992-1996	1997-1999	2003-2008
121.5 nm vs. SN	0.93	0.94	0.93	0.89	0.83
200.5 nm vs. SN	0.87	0.90	0.86	0.85	0.77
289.5 nm vs. SN	0.66	-0.28	-0.11	0.24	-0.72
300.5 nm vs.SN	0.18	0.34	0.50	0.06	-0.74

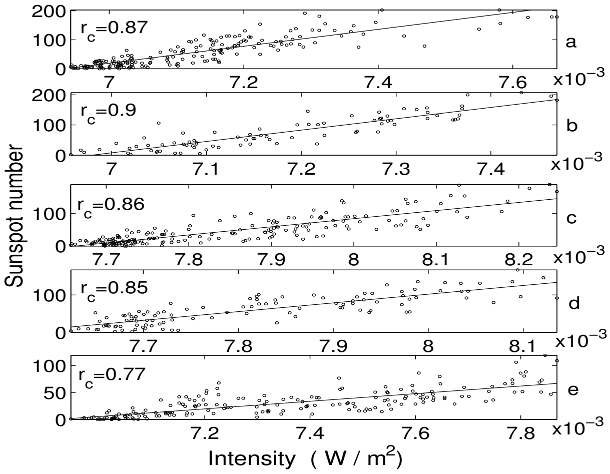

Figure 7: The same as in Figure 6 for 200.5 nm spectral line emission

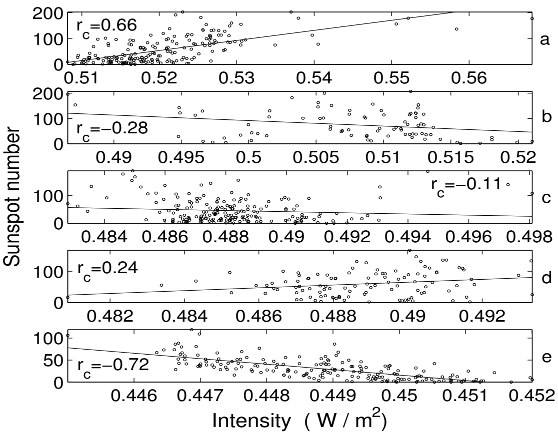

Figure 8: The same as in Figure 6 for 289.5 nm spectral line emission

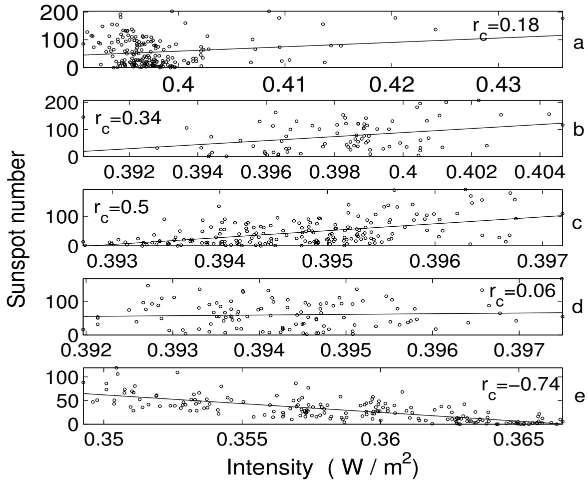

Figure 9: The same as in Figure 6 for 300.5 nm spectral line emission

Such a method of decomposition of solar irradiance necessarily implies a strong connection between the physical processes at different solar atmospheric layers (Ambrald et al., 2008).

Using contemporaneous helio-seismic data from GONG and MDI it is found that the changes in resonant mode frequencies during the current solar activity minimum period are significantly greater than the changes in solar activity as measured by different proxies. Further, both the GONG and MDI frequencies show a surprising anti-correlation between frequencies and activity proxies during the minimum between solar activity cycles 23 and 24 (Tripathy, 2010).

The frequencies of the global oscillation modes of the sun were used to learn about the seismic conditions of the solar interior during the current minimum phase. The variation of the oscillation frequencies with solar cycle has been the subject of many studies and is now well established. However, the physical origin of these changes is still an active field of research. The extended minimum activity epoch has provided an important period to analyze and interpret the frequency variations during quiet periods of solar activity (Tripathy, 2010).

Investigations of de Toma et al. (de Toma, 2001) illustrate the difficulty in using simple proxies and regression techniques to deduce physical sources of solar irradiance variability. According our study it is found that emission of different solar spectral narrow bands does not agree equally well with other indices of the solar activity during decreasing phase of the solar activity cycle 23. In some cases, high-level negative correlation takes place. We consider that obtained anti-correlation is not caused by changes of optical characteristics of measuring instruments, as an unusual behavior is observed in the range of solar spectral irradiance 289.5-305.5 nm. The occurrence of an anomalous behavior of some narrow bands of solar spectral irradiance complicates understanding of physical processes taking place in the Sun. If the cause of this anomalous behavior is intrinsic to the solar UV irradiance then a model for corresponding mechanism requires further improvement.

Furthermore, we have found anti-correlation between solar sunspot numbers and visual range intensity of solar spectrum near to Ca II K 393.36 nm and He I 587.59 nm belonged to chromospheric emission. Anti-correlation between appropriate helio-seismic frequencies and activity proxies during the minimum of the solar activity cycles 23-24 was revealed also according GONG and MDI data (Tripathy, 2010).

Table 3: Estimation of coefficients of linear fits for relationships between SSI and ISN for the solar activity cycles 21-23

Years		Coefficients of linear fits			
		121.5 nm	200.5 nm	289.5 nm	300.5 nm
1981-1986	A	(5.96 ± 0.17)x10^4	(2.93 ± 0.12)x10^5	(3.90 ± 0.32)x10^3	(1.57 ± 0.64)x10^3
	B	-233 ± 9	-23230 ± 85	-1974 ± 170	-570 ± 250
1987-1989	A	(7.60 ± 0.31)x10^4	(3.77 ± 0.20)x10^5	(-2.16 ± 0.83)x10^3	(7.41 ± 2.29)x10^3
	B	-286 ± 15	-2630 ±144	1170 ± 420	-2875 ± 900
1991-1996	A	(3.59 ± 0.10)x10^4	(2.51 ± 0.11)x10^5	(-2.09 ± 1.41)x10^3	(2.33 ± 0.29)x10^4
	B	-210 ± 7	-1920 ± 84	1070 ± 690	-9140 ± 1150
1997-1999	A	(3.94 ± 0.19)x10^4	(2.33 ± 0.14)x10^5	(4.51 ± 1.80)x10^3	(1.93 ± 3.23)x10^3
	B	-231 ± 14	-1760 ± 110	-2140 ± 880	-701 ± 130
2003-2008	A	(3.31 ± 0.16)x10^4	(7.07 ± 0.43)x10^4	(-1.24 ± 0.09)x10^4	(-3.71 ± 0.25)x10^3
	B	-190 ± 10	-500 ± 30	5600 ± 400	1360 ± 90

Revealed negative correlations between sunspot number and some solar spectral narrow bands of UV emission (289.5 nm, 300.5 nm), spectral lines (393.36 nm, 587.59 nm belonged to the visible range of solar spectrum), helio-seismic data (obtained by GONG and MDI) indicate that they are in close connection with the super-granules and plages. So the existence of the negative correlation can be explained by the reason that these objects are sensitive to the solar magnetic fields.

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