THE CYCLIC VARIATION OF SOLAR PHOTOSPHERIC INTENSITY FROM SOHO IMAGES

Dong-Gwon Jeong[1], Hyungmin Park[2], Byeongha Moon[1], and Suyeon Oh[1]

[1]Department of Earth Science Education, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 61186, Korea
suyeonoh@chonnam.ac.kr
[2]National Youth Space Center, 200 Deokheung yangjjokgil, Goheung, Jeollanam-do 59567, Korea

Abstract: The well-known solar cycle controls almost the entire appearance of the solar photosphere. We therefore presume that the continuous emission of visible light from the solar surface follows the solar cyclic variation. In this study, we examine the solar cyclic variation of photospheric brightness in the visible range using solar images taken by the Solar and Heliospheric Observatory (SOHO)/Michelson Doppler Imager (MDI). The photospheric brightness in the visible range is quantified via the relative intensity acquired from in the raw solar images. In contrast to total solar irradiance, the relative intensity is out of phase with the solar cycle. During the solar minimum of solar cycles 23–24, the relative intensity shows enhanced heliolatitudinal asymmetry due to a positive asymmetry of the sunspot number. This result can be explained by the strength of the solar magnetic field that controls the strength of convection, implying that the emission in the visible range is controlled by the strength of convection. This agrees with the photospheric brightness increasing during a period of long spotless days.

Key words: Sun: activity — Sun: photosphere — sunspots

1. INTRODUCTION

The solar atmosphere exhibits diverse changes over time, as shown by the sunspots on the photosphere. Sunspots are easily distinguished from the photosphere and can be used to predict the solar activity. They indicate the periodic features and degree of solar activity. The large sunspots affect the photospheric intensity during the solar cycle (Albregtsen & Maltby 1981).

Another notable feature of the photosphere is its center-to-limb variation, known as limb darkening (Appenzeller & Schröter 1967; Auffret & Muller 1991). Appenzeller & Schröter (1967) examined the variation of intensity from the solar center to the limb. The limb temperature differences between the poles and the equator do not exceed 6 K.

White & Livingston (1978, 1981) analyzed the chromospheric variability using the intensity of Ca II K lines. The strong Ca II and Mg II lines have been studied as spectroscopic diagnostics for solar chromospheres (Linsky 1977). They found that the variability in the Ca II lines for the full solar disk agrees with the solar activity with a mean intensity increase of 30% from solar minimum to solar maximum. They also attributed the changes in the K line to the addition of active region emission.

Heath & Schlesinger (1986) showed that the Mg 280 nm doublet emission correlates with solar UV irradiance and can be used for characterizing the effects of solar radiation on the atmosphere. The Mg II core-to-wing ratio at 280 nm is a good proxy for solar activity (Vierek & Puga 1999). Using data from multiple satellites, Vierek & Puga (1999) showed that it follows the solar cycle.

Several studies (Schmahl & Kundu 1994; Lee et al. 1995; Kononovich & Mironova 2006) showed that the total solar irradiance exhibits a solar cyclic variation and is a good indicator of solar activity. Pap et al. (2002) reviewed the long-term variations in total solar irradiance and spectral irradiances, including the Mg II center-to-wing ratio. Total irradiance and magnetic field strength show a shift in relative phase, with total irradiance leading the magnetic field strength during solar cycles 22–23. Pap et al. (1999) examined short-term variations in the VIRGO spectral and total irradiance data and noted that both parameters correlated well with each other.

In order to assess the relative importance of continuum and spectral-line variation in producing variations in irradiance, Unruh et al. (1999) calculated facular and sunspot contrasts as functions of wavelength and limb angle on the Sun. They suggested that the variation of continuum contributes negligibly to the variation of total irradiance on the time scale of solar cycles.

Nakakubo & Hara (2000) and Hara & Nakakubo-Morimoto (2003) counted the number of X-ray bright points (XBPs) and found that it is anti-correlated with the sunspot number due to a change of background X-ray intensity. Using a limited X-ray intensity range and removing the bias introduced by selecting an intensity threshold for XBP counting, they concluded that the number density of XBPs is independent of the 11-year solar cycle activity. Oh & Kim (2013) showed that many solar interplanetary geomagnetic (SIG) param-
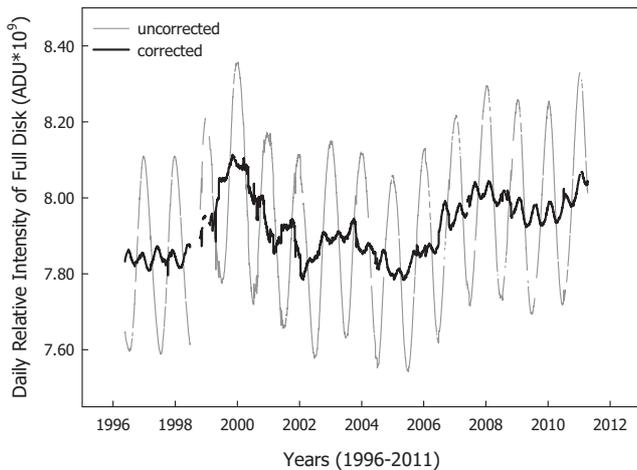
CORRESPONDING AUTHOR: S. Oh

Figure 1. Daily relative intensity of the solar full disk for the entire analysis period. Dark gray and thick black lines indicate the uncorrected and corrected relative intensities observed by SOHO, respectively.
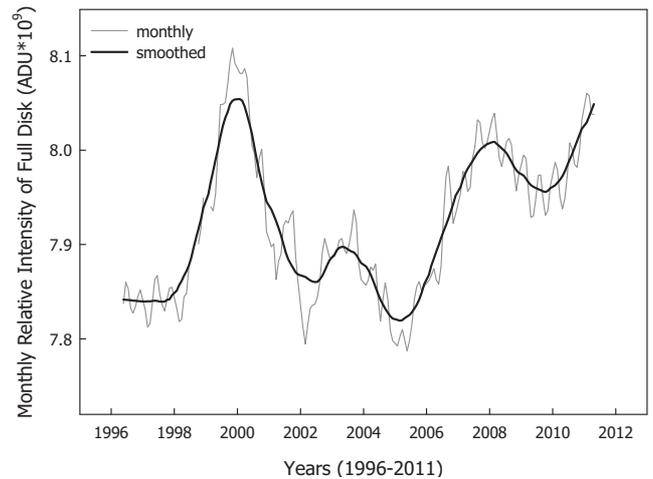

Figure 2. Monthly relative intensity of the solar full disk for the entire analysis period. Dark gray and thick black lines indicate monthly and smoothed monthly relative intensities observed by SOHO, respectively.

eters show solar cyclic variations. However, some solar parameters or features of solar appearance, i.e., solar activity, do not have any association with sunspot number, as demonstrated by the results of Nakakubo & Hara (2000) and Hara & Nakakubo-Morimoto (2003).

In this study, we examine the solar cyclic variation of photospheric brightness in the visible range using solar images taken by the Solar and Heliospheric Observatory (SOHO) over a total period from 1996 to 2011. We analyze whether or not the spectral irradiance of visible emission follows the solar cycle, as total solar irradiance does. Additionally, we explain the observed features of photospheric brightness during the solar cycle.

2. DATA AND METHODS

We estimated the photospheric brightness from 1024×1024-pixel full disk images taken with SOHO's Michelson Doppler Imager (MDI; Scherrer et al. 1995) obtained between May 1996 and April 2011. The intensity reference wavelength was 6768 Å. The relative intensity of the full disk is calculated by summation over all image pixels. For quantifying the asymmetry of the relative intensity, pixel values were read out along a one-pixel wide line from pole to pole. In order to determine the 24-hour variation, we analyzed the relative intensity during three days from October 30 to November 1, 2010. Since the variation of relative intensity within one day is insignificant, we selected one solar image per day, each taken at approximately the same time (near 00:00 UT). The relative intensity of solar photospheric brightness is given in units of "Analog to Digital Unit" (ADU). We also analyzed sunspot number, spectral irradiance, and solar mean magnetic field, using data from other sources, as discussed in Section 3.

The observed solar brightness is inversely proportional to the square of the distance between the Sun and the Earth. The average earth–sun distance is 149.6 million km and varies every day from a minimum on

January 4 (perihelion) to a maximum on July 6 (aphelion). Thus, we used a geometric correction to account for the seasonal change in observed brightness.

Figure 1 shows the daily relative intensity of the solar full disk for the entire analysis period. Dark gray and thick black lines indicate the geometrical uncorrected and corrected relative intensities by SOHO, respectively. The relative intensity shows a sinusoidal variation resulting from the seasonal variation. After geometric correction, the sine-wave variation is substantially reduced. The relative intensity follows the solar cyclic variation in early solar cycle 23 and is out of phase with the solar cycle thereafter. This feature also appears in Figure 2 which shows the monthly relative intensity of the solar full disk for the entire analysis period. Dark gray and thick black lines indicate monthly and smoothed monthly relative intensities as observed by SOHO, respectively. This issue will be discussed in Section 3.

3. RESULTS

3.1. Heliolatitudinal Asymmetry of Relative Intensity

Figure 3 shows the yearly relative intensities per SOHO/MDI pixel. The yearly relative intensity has a minimum at the solar minimum year of 1996 and then increases with the approach of the solar maximum. However, the solar minimum of 2008 is higher than that of 1996. The heliolatitudinal asymmetry of the relative intensity is negligible during the increasing phase of solar cycle 23 and appears enhanced since the solar maximum of solar cycle 23.

To examine the heliolatitudinal asymmetry in detail, we calculated the asymmetries of relative intensity and sunspot number; the results are shown in Figure 4. The dotted lines in both panels of the figure indicate zero asymmetry in sunspot numbers. The asymmetry of sunspot number was estimated from the monthly hemispheric sunspot number (SILSO; http:
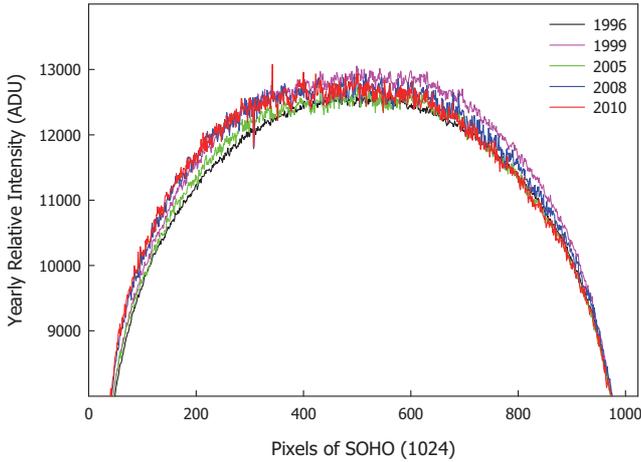
Figure 3. Yearly relative intensity per SOHO/MDI pixel. The total number of pixels is 1024 along a line from north to south pole.

//sidc.oma.be/silso/datafiles) and converted to yearly values. The asymmetry is defined as

$$\left(\frac{N}{Total} - \frac{S}{Total} \right) \times 100\% \; .$$

The positive asymmetry of the relative intensity indicates that the relative intensity is always larger in the northern hemisphere than in the southern hemisphere. The asymmetry of relative intensity remains low during the increasing phase of solar cycle 23 but then increases in the declining phase of solar cycle 23. During the solar minimum of solar cycles 23–24, it shows a large increase. The asymmetry of sunspot number shows a similar trend. Its sign turns from positive to negative after the solar maximum of solar cycle 23. During the solar minimum period of solar cycles 23–24, its sign changes from negative to positive and its amplitude reaches an all-time high. The positive asymmetry of the sunspot number induces the large asymmetry of relative intensity during the solar minimum period of solar cycles 23-24. Consequently, the solar northern hemisphere contributes greatly to the increase of relative intensity whereas the solar southern hemisphere shows little variation in relative intensity. This feature is more evident in the relative intensity shown in the bottom panel of Figure 4. The occurrence of sunspots in the northern hemisphere leads the increase of relative intensity. Accordingly, the evolution of the solar magnetic field, as indicated by the sunspot number and the relative intensity, is out of phase with the solar cycle. This issue is discussed below.

3.2. Comparison with SORCE Spectral Irradiance

Contrary to expectation, the relative intensity does not follow the solar cycle after the solar maximum of solar cycle 23. To support our result, we have to check the relative intensity for observational errors. Therefore we also analyzed the solar spectral irradiance data obtained by the Solar Radiation and Climate Experiment
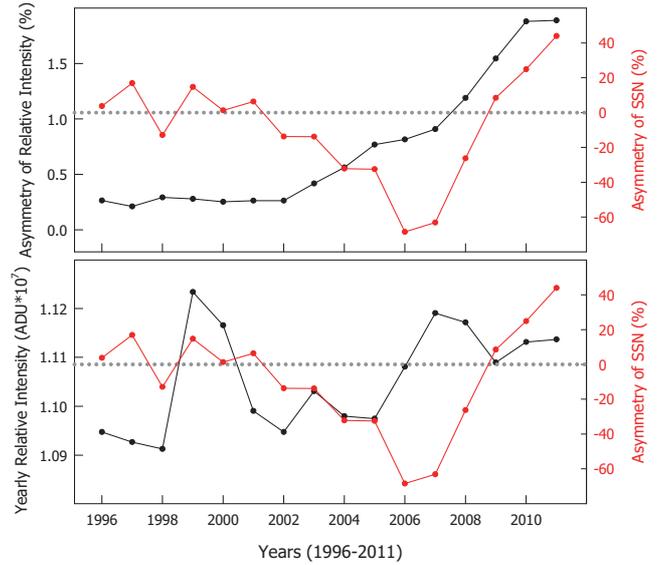

Figure 4. Heliolatitudinal asymmetries of relative intensity and sunspot number. *Top panel:* Both asymmetries shown together. Black and red lines represent the asymmetries of relative intensity and sunspot number, respectively. *Bottom panel:* The yearly relative intensity (black) and asymmetry of sunspot number (red).

(SORCE). Figure 5 shows the monthly solar spectral irradiance in ultraviolet and visible light. The SORCE wavelengths of 280.50 nm and 394.93 nm approximately correspond to the Mg II and Ca II K lines. The spectral irradiances at these wavelengths track the solar cyclic variations. However, the emission at 677.78 nm shows a steady increase since 2003, instead of following the solar cyclic variation. This wavelength band agrees with the intensity reference wavelength of SOHO. (The rest of the visible range, which is not shown here, also shows a gradual increase.) Therefore, our SOHO result – the relative intensity is out of phase with the solar cycle – agrees with the SORCE data. Even though the scales of relative intensity and solar spectral irradiance are different, the increase since the solar maximum of solar cycle 23 shows the same trend.

3.3. Relationship between Absolute Solar Mean Magnetic Field and Relative Intensity

Figure 6 shows the monthly sunspot number (SSN, top panel), absolute solar mean magnetic field (absolute SMMF, center panel), and relative intensity of the solar full disk (RI, bottom panel). Solar mean magnetic field data are from the Wilcox Solar Observatory. The relative intensity may be controlled by the absolute solar mean magnetic field rather than sunspot number. The smoothed values tell us that the relationship between absolute solar mean magnetic field and relative intensity depends on the strength of solar magnetic field. The period of 1996–2011 exhibits two solar minima and the second peak at the solar maximum is larger than the first peak. This trend appears simultaneously for both sunspot number and absolute solar mean magnetic
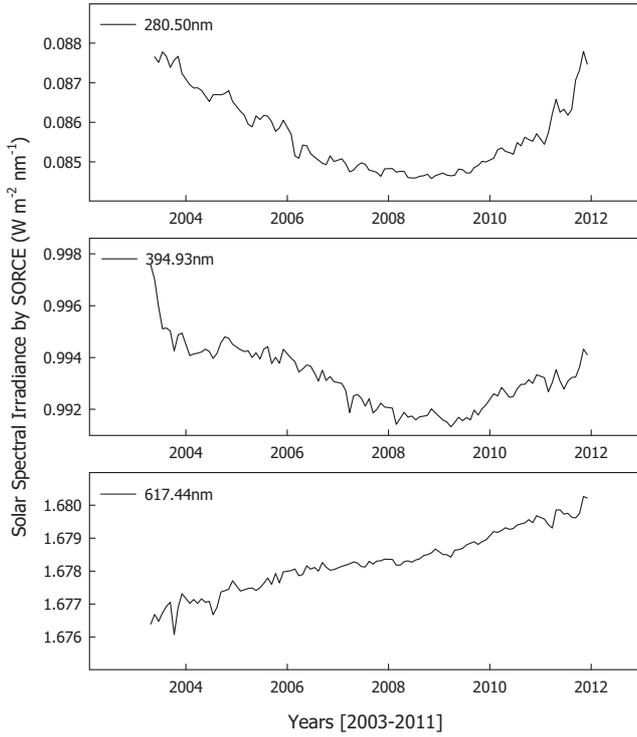
Figure 5. Monthly solar spectral irradiance observed by SORCE since 2003 in three wavebands.

Figure 6. Monthly sunspot number *(top panel)*, absolute solar mean magnetic field *(center panel)*, and relative intensity of the full solar disk *(bottom panel)*. Thick lines indicate smoothed versions of the corresponding curves.

field. The relative intensity follows the absolute solar mean magnetic field during the increasing phase when the first peak emerges. On the contrary, the relative intensity shows an anti-correlation with the absolute solar mean magnetic field in the declining phase when the second and larger peak appears. This relationship becomes clear in Figure 7.

Figure 7 shows the relationship between absolute solar mean magnetic field and relative intensity in the increasing (top panel) and declining (bottom panel) phases of solar cycle 23. The correlation between both parameters is positive in the increasing phase and negative in the declining phase.

4. DISCUSSION AND SUMMARY

In this study, we examine the solar cyclic variation of photospheric brightness in the visible range using solar images taken by SOHO. We also analyze the SORCE solar spectral irradiance, sunspot number, and absolute solar mean magnetic field. We find the following results:

1. Around the solar minimum of solar cycles 23–24, the enhanced heliolatitudinal asymmetry of the relative intensity is in good agreement with the asymmetry of the sunspot number. The positive asymmetry of the sunspot number induces the large asymmetry of the relative intensity. Consequently, the solar northern hemisphere contributes greatly to the increase of relative intensity.

2. Comparison with SORCE spectral irradiance data shows that the ultraviolet irradiance follows the solar cyclic variation. However, the emission in the
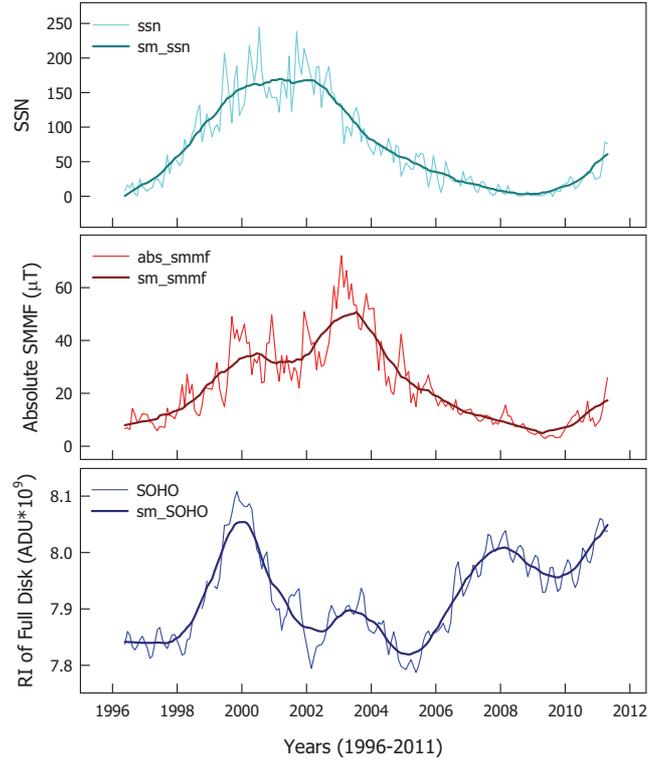
visible range shows a steady increase since 2003. This agrees with the results by Nakakubo & Hara (2000) and Hara & Nakakubo-Morimoto (2003) who found that some solar parameters do not exhibit a solar cyclic variation.

3. The strength of the magnetic field controls the relative intensity in the visible range. Since the moderate magnetic field in the increasing phase can help the emission of visible light, the relative intensity increases with the growth of the magnetic field. On the contrary, the limitation by the strong magnetic field in the declining phase induces a negative correlation between magnetic field and relative intensity.

Actually, we expected the relative intensity to follow the solar cyclic variation. However, it is in phase with the solar cycle in the increasing phase only and out of phase with the solar cycle in the declining phase. Since the relative intensity data cover only one solar cycle, including the unusual solar minimum period of solar cycles 23–24, the findings of the present study cannot be generalized to other solar cycles. The increase of relative intensity near the solar minimum of solar cycles 23–24 could not be explained in detail. However, we suspect that the long spotless days in that period induced a weak solar magnetic field. This encouraged the amount of hot material (which emits the visible light) transported to the surface. Indeed, the relative intensity tends to decrease
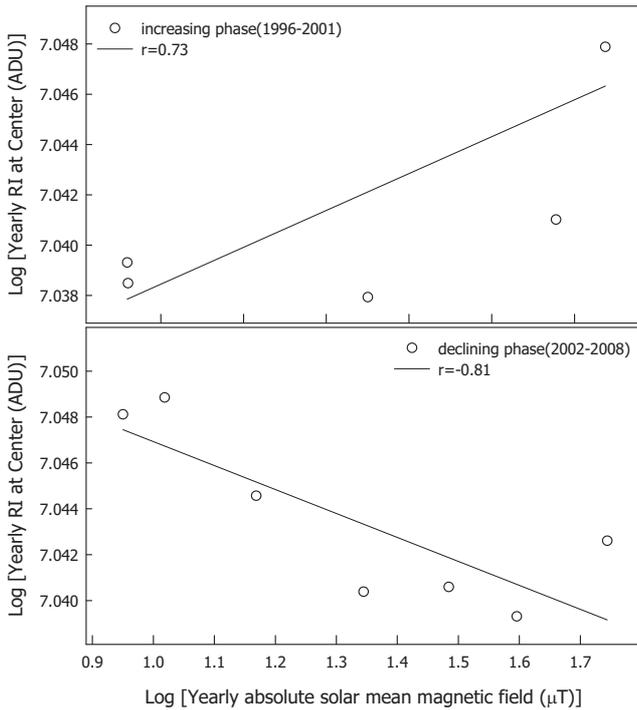
Figure 7. Relationship between absolute solar mean magnetic field and relative intensity in increasing *(top panel)* and declining *(bottom panel)* phases of solar cycle 23.

in early 2010, when sunspots appear frequently again.

Recently, Moon et al. (2017) examined the variation of the solar limb darkening coefficient estimated from SOHO/MDI and Solar Dynamics Observatory (SDO)/Helioseismic and Magnetic Imager (HMI) images. Their results show that the limb darkening coefficient shows a gradual increase since the solar minimum of 2008. This increase is due to an increase in photospheric intensity at the limb rather than at the center since 2008. This result can also explain the increase of relative intensity near solar minimum of solar cycles 23–24.

REFERENCES

Albregtsen, F., & Maltby, P. 1981, Solar Cycle Variation of Sunspot Intensity, Sol. Phys., 71, 269

Appenzeller, I., & Schröter, E. H. 1967, Center-to-Limb Variations of the Intensity and the Wavelength of Several Fraunhofer Lines along the Sun'S Polar and Equatorial Diameter, ApJ, 147, 1100

Auffret, H., & Muller, R. 1991, Center-to-Limb Variation of the Network Bright Points in the Solar Photosphere, A&A, 246, 264

Hara, H., & Nakakubo-Morimoto, K. 2003, Variation of the X-Ray Bright Point Number over the Solar Activity Cycle, ApJ, 589, 1062

Heath, D. F., & Schlesinger, B. M. 1986, The Mg 280-nm Doublet as a Monitor of Changes in Solar Ultraviolet Irradiance, JGR, 91, 8672

Kononovich, E. V., & Mironova, I. V. 2006, The Wolf Number and Total Solar Irradiance Variations during 21–23 Solar Cycles, Astron. Astrophys. Transactions, 25, 341

Lee, R. B. III., Gibson, M. A., Wilson, R. S., et al. 1995, Long-Term Total Solar Irradiance Variability during Sunspot Cycle 22, JGR, 100, 1667

Linsky, J. L. 1977, in O. R. White (ed.), The Solar Output and Its Variation (Boulder: Colorado Assoc. Univ. Press)

Moon, B., Jeong, D.-G., Oh, S., et al. 2017, Variation in Solar Limb Darkening Coefficient Estimated from Solar Images Taken by SOHO and SDO, J. Astron. Space Sci., 34, 99

Nakakubo, K., & Hara, H. 2000, Variation of X-Ray Bright Point Number over the Solar Activity Cycle, Adv. Space Res., 25, 1905

Oh, S., & Kim, B. 2013, Variation of Solar, Interplanetary and Geomagnetic Parameters during Solar Cycles 21-24, J. Astron. Space Sci., 30, 101

Pap, J., Anklin, M., Fröhlich, C., et al. 1999, Variations in Total Solar and Spectral Irradiance as Measured by the VIRGO Experiment on SOHO, Adv. Space Res., 24, 215

Pap, J. M., Turmon, M., Floyd, L., et al. 2002, Total Solar and Spectral Irradiance Variations from Solar Cycles 21 to 23, Adv. Space Res., 29, 1923

Scherrer, P. H., Bogart, R. S., Bush, R. I., et al. 1995, The Solar Oscillations Investigation - Michelson Doppler Imager, Solar Phys., 162, 129

Schmahl, E. J., & Kundu, M. R. 1994, Solar Cycle Variation of the Microwave Spectrum and Total Irradiance, Sol. Phys., 152, 167

Unruh, Y. C., Solanki, S. K., & Fligge, M. 1999, The Spectral Dependence of Facular Contrast and Solar Irradiance Variations, A&A, 345, 635

Viereck, R. A., & Puga, L. C. 1999, The NOAA Mg II Core-to-Wing Solar Index: Construction of a 20-Year Time Series of Chromospheric Variability from Multiple Satellites, JGR, 104, 9995

White, O. R., & Livingston, W. C. 1978, Solar Luminosity Variation. II – Behavior of Calcium H and K at Solar Minimum and the Onset of Cycle 21, ApJ, 226, 679

White, O. R., & Livingston, W. C. 1981, Solar Luminosity Variation. III – Calcium K Variation from Solar Minimum to Maximum in Cycle 21, ApJ, 249, 798