

The Relationship between Solar Activity and Geomagnetic Activity Indices in the Last Four Solar Cycles

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Abstract

In this study, Lyman-alpha solar spectral irradiance (SSI) compared with geomagnetic Ap, Dst and PC index time series for the time period of 1975-2020. All data sets used in this study are taken from OMNIWeb. To compare Lyman-alpha SSI and geomagnetic indices cross correlation and Morlet wavelet analysis methods were used. In results of our analysis we found following results: i) Selected geomagnetic activity indices weakly correlated with Lyman-alpha SSI index. ii) The Lyman-alpha SSI is ahead of all geomagnetic activity indices except Dst index. iii) All indices used in this study show 11 year solar cycle and 27 day solar rotation periodicities.

Introduction

The sun is the largest radiation source continually affecting near space environment with a flow of charged particles, known as the solar wind, originating from its outer layer. Although the sun is a quiet star compared to other stars, many active structures are observed with detail due to its nearness to earth. When the temporal variations of these structures are investigated, it can be evaluated that the sun is a quasiperiodic star. All time and location dependent changes observed on the sun can be defined as solar activity. The best known indicators of solar activity are sunspots and solar flares.

There are several periodic variations of solar activity. The most well-known of these variations are the 27-day solar rotation and the 11-year sunspot cycle. The longest-running and most common dataset used to study the solar cycle is sunspot numbers. Since about 1610, sunspots have been systematically observed by using telescopes. The other datasets used are sunspot area, 10.7 cm solar radio flux (F10.7), Lyman-alpha SSI, solar flare index (FI), and coronal mass ejections (CMEs), etc. Generally, all solar activity indicators are strongly correlated with each other (Hathaway et al., 2002).

Geomagnetic storm is defined as irregularities in the Earth's total magnetic field. These irregularities are also show differences with time and location. Various indices are used to measure these irregularities such as AE index, K index, Dst index, PC index. The relationship between geomagnetic indices depends on the evolution of solar activity and there are strong losses in the correlation between geomagnetic activity indices during the declining phases of the 20th and 23rd solar cycles. Geomagnetic activity indices also have a certain level of correlation both with each other and with solar activity (Verbanac et al., 2011).

The most important feature of the aa time series is its double-peak structure (Gonzalez et al., 1990). The first peak of this double structure is caused by coronal mass ejections associated with solar activity, while the second peak is caused by the high speed streams originate from coronal holes located at the polar regions of the sun (Gonzalez et al., 1990).

Russell and Mulligan (1995) obtained a significant correlation between the aa index and the solar polar magnetic field for the time period of 1868 to 2006. The highest correlation between monthly solar activity and geomagnetic indices were observed between solar wind and Ap index ($r = 0.76$) and Dst index ($r = 0.52$) with zero-time delay (Kilcik et al., 2017). In addition, Mursula and Zeiger (2000) found 1.3 years periodicity between solar wind and Ap indices in even cycles, while they found 1.5-1.7 years periodicity in odd cycles. Although the relationship between the solar activity and geomagnetic activity indices has been extensively

studied, a detailed explanation of their nature has not yet been clearly given (Echer et al., 2004; Verbanac et al., 2011).

In this study, a time series analysis was performed using data obtained for the last four solar cycles (1975 – 2020). We describe data and methods used in Section 2, analysis and results are given in Section 3, finally the discussion and conclusions are given in Section 4.

Data and Methods

a) Data

In this study we used Lyman-alpha SSI index as solar activity index and Dst, Ap and PC(N) indices were used as geomagnetic activity indices.

The Lyman-alpha line is hydrogen's strongest emission line at 121,567 nm and it describes the full disc integrated solar irradiance over 121-122 nm wavelength interval. The composite Lyman-alpha SSI data used in this study was taken as daily form from OMNIWeb.

Figure 1 shows the temporal variation of sunspot number and Lyman-alpha SSI index. Considering the sunspots number as a very good index of solar activity, it is clearly seen from the figure that the Lyman-alpha SSI index also represents the solar activity quite well.

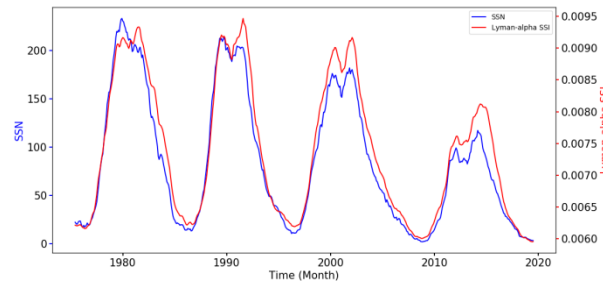


Fig.1. Comparison of SSN and Lyman-alpha SSI

The F10.7 radio flux is a commonly used index of solar activity (Tapping, 2013). Barth et al. (1990) found a high correlation between the Lyman-alpha SSI index and F10.7 radio flux in the ascending and descending phases of the sunspot cycle over a 200-day or longer time period. Based on their results and the temporal variation between the sunspots number and the Lyman-alpha SSI index (Figure 1), the Lyman-alpha SSI index was used as an index of solar activity in this study.

Dst (Disturbing Storm Time) index it allows to investigate the symmetrical axis situation of magnetospheric currents, especially ring currents. This index, which is directly relevant to geomagnetic activity, is also known as the vertical component of the magnetic field. Data from four observatories are used to derive the Dst index. Because of good data quality these observatories were chosen sufficiently far from the auroral and equatorial electrojet regions. Irregularities observed in the Dst index have a negative sign and $-50 \text{ nT} \leq \text{Dst} < -30 \text{ nT}$ are called small storm, $-100 \text{ nT} \leq \text{Dst} < -50 \text{ nT}$ are called moderate storm, $-200 \text{ nT} \leq \text{Dst} < 100 \text{ nT}$ are called intense storm and values less than -250 nT are called big storms (Gonzalez et al., 1999).

The K index is used to measure changes in the horizontal component of the magnetic field. However, on the grounds that K index is not directly related to geomagnetic activity. Thus, produce an activity-related index was required. Therefore, first, the Kp index was derived from the mean standardized K-index of 13 geomagnetic observatories located between ± 44 and 60 degrees geomagnetic latitudes. This planetary index is designed to measure the magnetic effect of solar particle radiation. The 3-hourly ap index is derived from the Kp index by using following table (Table 1). Then, the daily Ap index value is obtained by averaging the eight values of ap for each day.

Table1. Derivation table of the *ap* index from *Kp* index given by J. Bartels
(https://www.ngdc.noaa.gov/stp/GEOMAG/kp_ap.html)

<i>Kp</i> = 0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
<i>ap</i> = 0	2	3	4	5	6	7	9	12	15	18	22	27	32
<i>Kp</i> = 5-	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
<i>ap</i> = 39	48	56	67	80	94	111	132	154	179	207	236	300	400

PC index, it is an index improved to predict the instantaneous state of global magnetic activity and to easily calculate it from ground based measurements. Basically to calculate this index, the concept of convection in the near polar region controlled by solar wind parameters is considered. Quiet periods of ionospheric conductivity are selected for each day of the year from Thule (PC- North) and Vostok (PC-South) to exclude the daily and seasonal variation of ionospheric conductivity produced by the solar ultraviolet radiation (Troshichev et al., 2006). In the statistics made as a result of the agglomerated data, it shows that the PC index is a good index for magnetospheric parameters such as auroral electrojets, ionospheric electric field in the near polar region, etc.

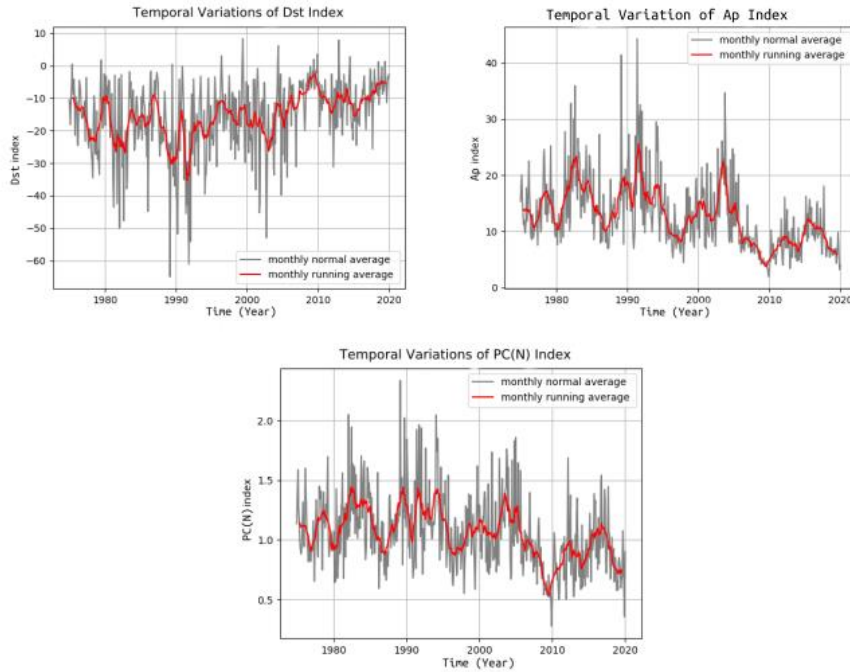


Figure2. Temporal variations of geomagnetic *Dst*, *Ap* and *PC(N)* indices.

b) Methods

All data sets used in this study were taken as daily form from OMNIWeb for 1975-2020 time intervals. Then monthly data sets were produced. In order to eliminate the small fluctuations in these monthly data, the data sets smoothed with 12-step running average smoothing method. Then, the cross-correlation analysis method was applied to obtain the highest correlation coefficients with possible time delay between the Lyman-alpha SSI index and geomagnetic activity indices used in this study.

Morlet wavelet analysis method was applied to determine the possible periodicities with their occurrence time. This technique is becoming a valuable method to analyze localized variations of power within a given time series (Torrence and Compo, 1998). It has been widely used in the literature for different kind of time series such as astronomical (Kilcik et al., 2020), geophysical (Torrence and Compo, 1998), etc. In this study, Lyman-alpha SSI index and *Ap*, *Dst* and *PC(N)* geomagnetic activity indices analyzed and the scalograms were obtained to

address the presence of the detected periodicities. We have used “Morlet” mother function considering a “red noise” background (Torrence and Compo, 1998). The edge effects is represented by the cone of influence (COI) plotted with a black line in the figures shown below. On the other hand, the periods detected above the 95% confidence level inside the COI are shown by black contours in these figures.

Analysis and Results

Figure 3 plots the cross correlation analysis results between solar and geomagnetic activity indices used in this study. The detailed results of the correlation analysis are given in Table 2.

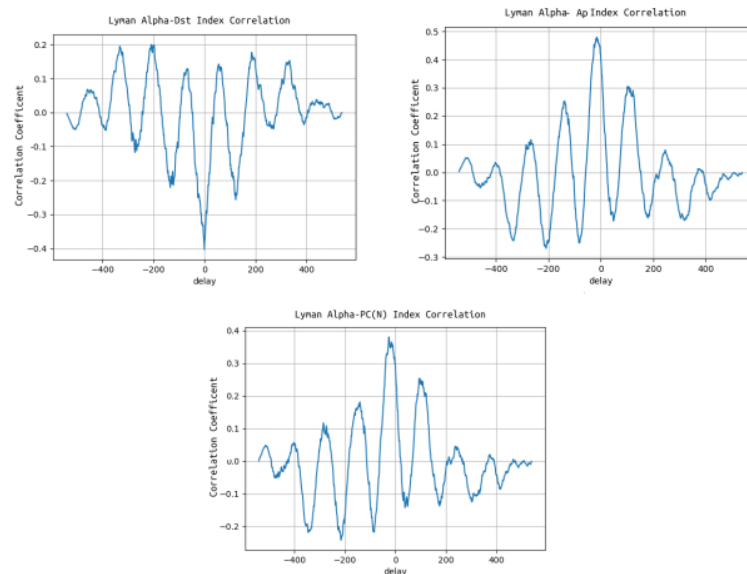


Figure3. Dst, Ap and PC(N) index cross-correlation results with Lyman-alpha SSI

Table2. Cross-correlation coefficients and their corresponding time delays

	Lyman-alpha SSI-Dst	Lyman-alpha SSI-Ap	Lyman-alphaSSI-PC(N)
Cross Correlation Coefficient	-0.40±0.04	0.42±0.04	0.30±0.04
Time Delay (Month)	0	14	25

As shown in Figure 3 and Table 2, geomagnetic Ap index and Dst index show the same level of correlation with Lyman-alpha SSI index. The Ap index correlation looks a bit higher than the Dst correlation but it has 14-month time delay compared to Dst and this time delay does not any meaning. Thus we may suggest that the Dst index better describe the Lyman-alpha SSI index. The lowest correlation and largest time delay obtained between PC(N) and Lyman-alpha SSI index.

Figure 4 shows the period analysis results of solar and geomagnetic activity indices used in this study.

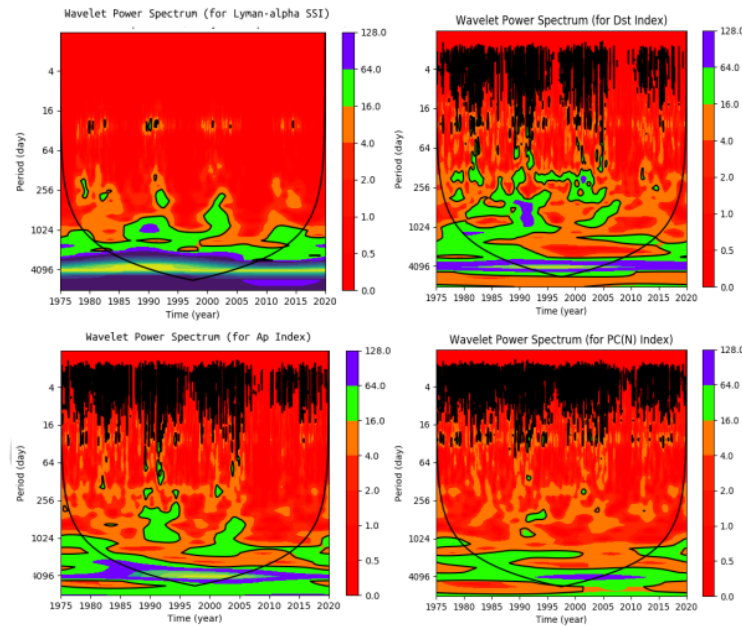


Figure 4. The Morlet wavelet analysis results for the used data sets.

As shown in Figure 4, about 11 years solar cycle periodicity clearly seen in the Morlet wavelet scalograms of all data sets for the investigated time period (from 1975 to 2020) except PC(N) index that it only seen between 1993-2013 time interval. 27 days solar rotation periodicity is also clearly seen in the wavelet scalogram of all data sets especially during the maximum phases of solar cycles. A 1024 days periodicity is seen in all data sets used in this study without any exception and it appears around the maximum phases. The one another meaningful period in the wavelet spectrum are about 1800 days for the PC(N) index and it seen around 1975-2000 and 2010-2020 time intervals. About 500 days periodicity is appear in all geomagnetic activity indices; it only seen during the maximum phases of solar cycles 22 and 23. A 256 days periodicity appear in all data sets except PC(N) index. It is clearly seen especially during the maximum phases of cycles 22 and 23.

Discussion and Conclusions

In this study, we investigated the correlation and periodicity relationship between solar (Lyman-alpha SSI and geomagnetic activity indices (Ap, Dst and PC(N)) for the 1975 – 2020 time periods. Our main findings are as follows;

1. Selected geomagnetic activity indices weakly correlated with Lyman-alpha SSI index,
2. The Lyman-alpha SSI index is ahead of all geomagnetic activity indices except Dst index.
3. All indices used in this study show about 11 year solar cycle and 27 day solar rotation periodicities.

Kilcik et al. (2017) obtained remarkable correlations between the geomagnetic Ap and Dst indices and different categories of sunspot counts. As shown in Figure 1 sunspot number and Lyman-alpha SSI index are well correlated. Thus, we may expect that the Lyman-alpha SSI index show some level of correlation with geomagnetic indices used in this study. As expected, we found that the Lyman-alpha SSI index and geomagnetic activity indices are weakly correlated ($r = -0.40$, $r = 0.42$ and $r = 0.30$) with Ap, Dst and PC(N), respectively. Verbanac et al. (2011) found that the Dst index has zero time lag and Ap index has 1-2 year time lag with used solar activity indices. Here, we confirm their results with Lyman-alpha SSI index. Kilpua et al (2014) analyzed Dst, Auroral Elektrojets (AE) and interplanetary magnetic field (IMF) between

1995-1999 and 2006-2012 and showed that there is very low geomagnetic activity during the solar cycle 24. Here, we also confirm their results as shown in Figure 2.

Mursula and Zieger (2000) found about 1.3 year periodicity for solar wind speed, geomagnetic activity indices and auroras. They conclude that this periodicity related to the evolution of coronal holes. In our study, we found about 500-day periodicity for all used geomagnetic activity indices which cover recent solar cycles. Thus we confirm their results and further suggest that this periodicity may be the general characteristics of geomagnetic activity.

Solar activity time series generally show a double/multiple peak structure during the maximum phase of cycles. The visible gap between peaks is called as the 'Gnevyshev Gap' (Bazilevskaya et al., 2006). Verbanac et al. (2010) suggested that the time delay between F10.7 and Dst index is less than one year and it is due to the Gnevyshev gap. They concluded that the response of Ap and Dst indices to solar activity are different; while Dst index is affected by coronal mass ejections, Ap index is more sensitive to high speed streams (HSS). We also found different time delays for different geomagnetic indices and confirm above results with recent data.

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