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SOLAR AND GEOMAGNETIC ACTIVITY IN 19-25 CYCLES

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ABSRACT. The paper presents the results of the analysis of changes solar and geomagnetic activity in 19−25 Wolf cycles. A forecast of the maximum geomagnetic activity cycle 25 is made.

Solar activity is presented by sunspot number R_Z, geomagnetic activity is expressed by the energetic index calculated from the data of the "Lviv" and "Belsk" geomagnetic observatories. By annual averages R_Z values, the 11-year window was used to obtain the solar activity minimum (around 1711, 1810, 1901, and 2009). The minimum of 2009 was one of the smallest in the observed data, and we took it as the beginning of the 24th cycle and the 100-year solar activity cycle. The maximum of the 24th cycle occurred in 2014 for R_Z and in 2015 for energetic index.

Cycle 25 began in 2019 according to R_Z, and in 2020 according to energetic index. For cycles 19−25 solar activity is 1−2 years ahead of magnetic activity. The identified quasi-biennial variations over the studied period and the lag of geomagnetic activity from solar activity allow us to predict the magnitude of geomagnetic activity and its maximum in cycle 25.

According to our calculations, the maximum of geomagnetic activity will occur around 2026 and its magnitude will be 1.5−2 times higher than the maximum of the 24th cycle.

Key words: Solar and geomagnetic activity, solar cycle.

АНОТАЦІЯ. У роботі викладено результати аналізу змін сонячної та геомагнітної активності у 19−25 циклах Вольфа. Зроблено прогноз максимуму геомагнітної активності у 25 циклі.

Сонячну активність виражено сонячними числами R_Z, геомагнітну активність виражено енергетичним індексом, вичисленим за даними геомагнітних обсерваторій «Львів» та «Бельськ». Усереднивш всі наявні річні значення R_Z, 11-річним біжучим вікном отримано мінімуми сонячної активності вікових циклів (близько 1711, 1810, 1901, 2009).

Мінімум у 2009р. був один з найменших у спостережуваних даних, прийнято нами за початок 24 циклу а також 100-літнього циклу сонячної актвності. Максимум 24 циклу наступив у 2014 році за R_Z, та у 2015 за енергетичним індексом. 25 цикл розпочався у 2019 році за R_Z, та у 2020 за енергетичним індексом. Протягом 19−25 циклів сонячна активність випереджає магнітну на 1−2 роки. Виділені квазідворічні варіації за досліджуваний період та відставання геомагнітної активності від сонячної дозволяють нам спрогнозувати величину геомагнітної активності та її максимум у 25 циклі.

За нашими розрахунками максимум геомагнітної активності наступить близько 2026 року а його величина буде у 1.5−2 рази більша за максимум 24 циклу.

Ключові слова: Сонячна і геомагнітна активність, сонячний цикл.

1. Introduction

Solar and geomagnetic activity (SA and GA) has been studied by many authors since the beginning of instrumental observations of the Sun and the Earth's magnetic field (Petrovay, 2020) for more than 500 years. However, a strong law of the relationship between the SA and the GA has not been established so far. Despite the use of satellite observations by humans, which has brought us several orders of magnitude closer to solving this problem. The main reason is that the Sun-Earth system is a nonlinear system. This is confirmed by the works of (Czernogor, 2008; Shuman, 2015), so there can be no single law or model of the relationship between the SA and the GA.

To show the relationship between SA and GA in 19−25 cycles of their development patterns and, on this basis, to make a forecast of GA for 25 SA. We used the data of SA expressed by R_Z and the values of the large-scale solar magnetic field (SMF), GA was expressed by the energy index describing the energy supplied from the solar wind to the magnetosphere during the studied period.

2. Solar activity

In this paper, the SA was expressed by two characteristics: the R_Z numbers taken from (https://www.sidc.be/SILSO/datafiles) and the sign of the Sun's large-scale magnetic field. It is known that the SA varies periodically: quasi-biennial variations (QBV), 11-year cycles (Schwabe-Wolf), 22-year cycles (Hale), 60−80-year cycles, 100-year cycles (Heisberg), 200-210-year cycles, and others. A characteristic feature of these cycles: for 11-year cycles, the Gnevyshev-Ohl rule, which means that even cycles are weaker in terms of the amplitude

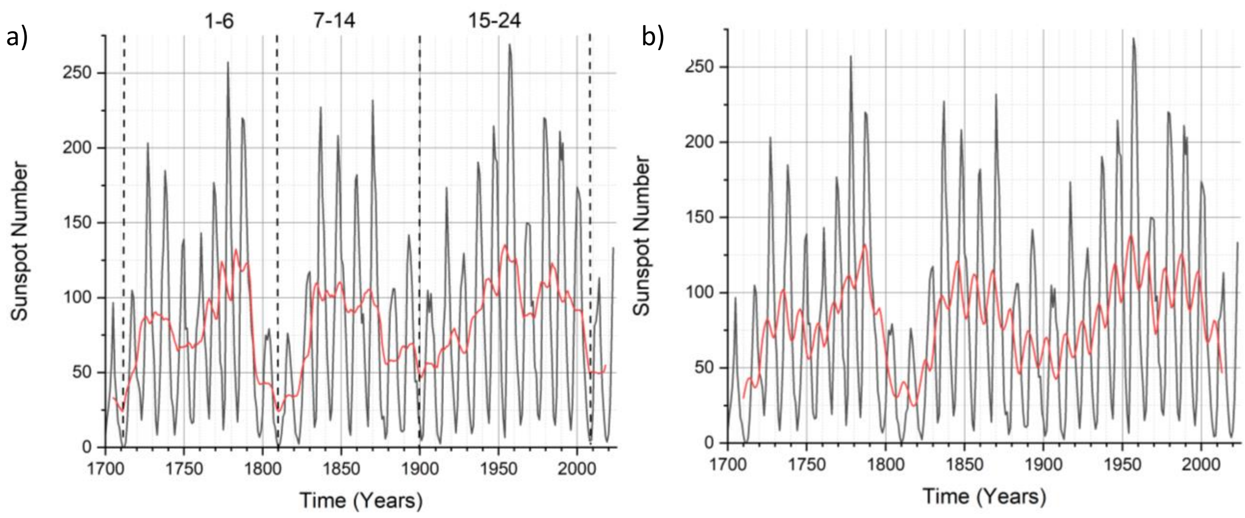

Figure 1: a) Yearly averages of sunspot number Rz (black lines), and a 11-year smoothed curve of Rz (red lines) for the interval 1700-2023; b) Yearly averages of sunspot number Rz (black lines), and a 22-year smoothed curve of Rz (red lines) for the interval 1700-2023.

Table 1: Periods of solar activity and the nature of their changes (years of the beginning, maximum and nature of changes in the SA cycles)

Period	beginning	Maximum	nature of changes in the SA
11	2019	2025	increasing
80–100	2009	2059	increasing
200– 210	1850	1956	decreasing
350 – 360	~1750	~1900	decreasing

of changes in solar numbers R_Z than the odd ones that follow them. Over the past 250 years, this rule has been violated in 4−5, 8−9, 22−23 SA; for 22-year Hale cycles, the sign of the SMF at the north pole of the Sun is characteristic; for the QBV the zug (duration) of oscillations is characteristic. Table 1 shows the periods of solar activity and the nature of their changes (years of the beginning, maximum and nature of changes in the SA cycles).

By averaging all available R_Z with an 11-year running window (red curve), we identified 100-year SA cycles (Fig. 1a). The minima (the beginning of the cycle) were observed in 1711, 1810, 1901, and 2009. In addition, in the 100-year SA cycles, we distinguish two-humped maxima with minima of 1SA, 11SA, and 20SA, which fall out of the general rule of SA growth in terms of amplitude (Krivodubskiy, 2016; Orliyuk & Romenets, 2023), in our opinion, this is a manifestation of a half-century cycle with a period of ~40−50 years. Averaging all the available R_Z with a 22-year running window (red curve), we similarly distinguish 100-year SA cycles (Fig. 1b) with the same SA minima (starts) as when averaging with an 11-year window. This pattern confirms the correctness of the definition of 100-year cycles. The last of the observed 100-year cycles began in 2009 with one of the lowest R_Z=4.2 for the entire observation period.

3. Geomagnetic activity

The geomagnetic activity in this study was expressed by the average annual values of the energy index $\sum(H - S_q)$ (Sumaruk & Sumaruk, 2007), determined from the data of the mid-latitude geomagnetic observatory "Lviv" and "Belsk". This index is quickly calculated from the data of mid-latitude geomagnetic observatories and characterizes the energy supplied from the solar wind to the magnetosphere (its corpuscular part) and correlates well with other GA indices such as K_p, AE, aa etc. (Sumaruk et al., 2012).

The physical meaning of the $\sum(H - S_q)$ index is as follows. The horizontal component (H) of the total magnetic induction vector B best reflects external sources of geomagnetic variations, therefore, it characterizes the magnetosphere-ionosphere current system well and therefore is proposed to be used to determine the GA. The solar diurnal variation (S_q) of the horizontal component (H) characterizes the wave radiation of the Sun. The integral sum $\sum(H - S_q)$ shows the field change caused by the corpuscular radiation of the Sun. By integrating this value over the required time interval, we obtain the characterization of the field disturbance over this interval.

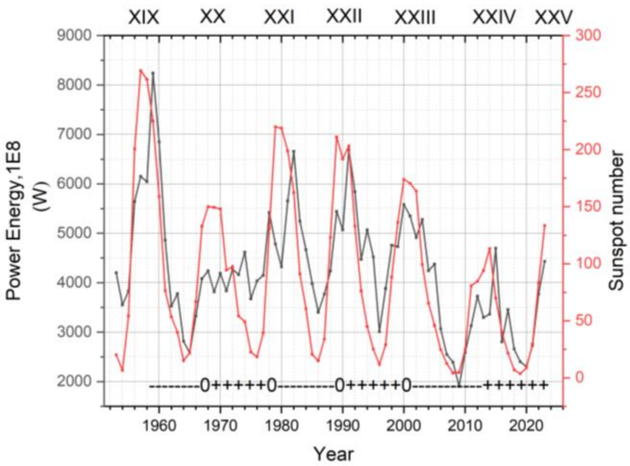

Figure 2: Values of the mean annual values of the energy (GA) entering the magnetosphere in 19-25SA (black curve), sunspot number R_z (red curve), and the sign of the SMF are presented.

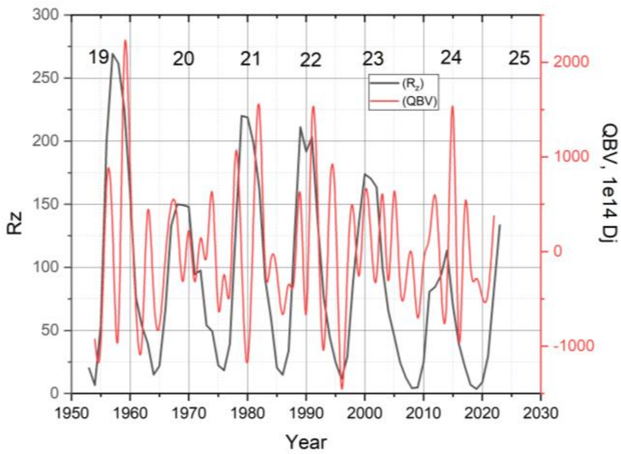

Figure 3: Quasi-biennial variations (red curve) of GA and solar activity (black curve) for 18-25 SA.

Table 2: Average monthly values of energy entering the magnetosphere during the years of minima (the beginning of 19-25 cycles) of SA and GA

Year	1955	1965	1975	1986	1996	2009	2020
E, Je14	3830	2576	3677	3403	3007	1908	2403

Using $\sum(H - S_q)$ as the GA index, we can quickly calculate the energy entering the magnetosphere from the solar wind based on the data of the mid-latitude observatory. The results of our calculations are in good agreement with those of other authors (Akasofu, 1981; Levitin, 2005; Chernogor, 2008; Echer, 2011).

Fig. 2 shows the values of the mean annual values of the energy (GA) entering the magnetosphere in 19−25SA (black curve), sunspot number R_Z (red curve), and the sign of the SMF are presented. The lag in the phase of the GA maxima from the SA by 1−2 years is clearly distinguished.

Table 2 shows the average monthly values of energy entering the magnetosphere during the years of minima (the beginning of 19−25 cycles) of SA and GA. This energy is directly proportional to the number of all geomagnetic disturbances that occurred in these years. The value of the average energy received during the 19−25 SA minima was the lowest in 2009. A similar result was obtained by the authors of (Hajra et al., 2014), which confirms the conclusions of other authors about the "small Maunder minimum" and extremely low GA in 24SA (Vaquero et al., 2011). A similar SA minimum was observed at the end of the nineteenth century, which is associated with the Heisberg cycle (Echer, 2012).

The number of recurrent geomagnetic disturbances was also characteristic for 19−24 SA. Recurrent disturbances were considered to be those that repeated two or more times in a 27-day cycle. The maximum recurrence for the studied period was observed in 2378−2395 revolutions of the Sun (according to Bartels) from November 23, 2007 to January 27, 2009. At this time, the number of solar flares was extremely low, although perturbations of the Earth's magnetic field were observed. Recurrent geomagnetic disturbances were repeated in 17 revolutions of the Sun. The disturbances occurred on days 1−4 and days 16−20 of the Barthelian rotation. Obviously, they were caused by recurrent long-term solar plasma flows (for example coronal holes, etc.) located at the active longitudes of the Sun. As shown in (Sumaruk, 2010), the ratio of the number of recurrent storms to the number of storms with sudden onset was maximum at the beginning of 24SA (1.5−4 times higher than the previous minimums of 19−23SA).

4. Quasi-biennial variations of geomagnetic activity

In the spectrum of SA expressed by a number of R_Z numbers or other indices, along with the other periods described above, the period 2−4 years is often distinguished (Gnevyshev, 1977; Apostolov, 1985). The same quasi-biennial variations (QBV) have been found in the parameters of the interplanetary environment (Okhopkov, 1998) and geophysical processes (Fadel et al., 2002). In the initial phase of the SA, the period of individual oscillations is more than three years, and in the minimum SA it is less than two years.

Since the QBVs are manifested in all parameters of solar activity, in variations of the solar wind and ionosphere, and in meteorological phenomena (Ivanov-Kholodny et al., 2003), we attempted to identify the QBVs in the variations of the geomagnetic field in the middle latitudes (Sumaruk & Sumaruk, 2009b). As the initial data of the magnetic activity measure we chose the monthly

Table 3: A selection of early forecasts for Cycle 25(Petrovay, 2020)

Category	Minimum	Maximum	Peak amplitude	References
Internal precursors	2019.9	2023.8	175 (154–202)	Li et al. (2015)
External precursor				
Polar precursor			117±15	Table 1 here
Polar precursor			136±48	Pesnell and Schatten (2018)
Helicity			117	Hawkes and Berger (2018)
SoDA		2025.2±1.5	120±39	Based on Pesnell and Schatten (2018)
Rush-to-the-poles	2019.4	2024.8	130	Petrovay et al. (2018)
Model-based: SFT				
SFT			124±31	Jiang et al. (2018)
AFT	2020.9		110	Upton and Hathaway (2018)
Model-based: dynamo				
2x2D	2020.5±0.12	2027.2±1.0	89±14	Labonville et al. (2019)
Truncated	2019–2020	2024 ± 1	90±15	Kitiashvili (2016)
Spectral				
Wavelet decomposition tree		2023.4	132	Rigozo et al. (2011)
Attractor analysis				
		2024.0 ± 0.6	103±25	Singh and Bhargawa (2017)
Simplex projection analysis				
Simplex proj./time- delay		2023.2 ± 1.1	154±12	Sarp et al. (2018)
Neural networks				
Neuro-fuzzy		2022	90.7±8	Attia et al. (2013)
Spatiotemporal		2022–2023	57±17	Covas et al. (2019)
Cycle 24 (comparison)	2008.9	2014.3	116	

average sums of deviations of the horizontal component of the magnetic field for a given year at the "Lviv" and "Belsk" geomagnetic observatories from the quiet level of the field $\sum(H - S_q)$. The quiet level is taken as the daily course of the same component averaged over five internationally quiet days for each month. Since the amplitudes of S_q-variations change with the season, seasonal variations of activity caused by changes in the ionospheric conductivity are excluded in the values $\sum(H - S_q)$.

To identify the QBV in GA, we used the methodology proposed in (Ivanov-Kholodny & Chertoprud, 1992) for identifying the QBV in SA, which consists in subtracting the value of the selected parameter for the same month in the previous and next year from the double monthly average value of the selected parameter.

In Fig. 3 shows the QBV (red curve) of GA and SA (black curve) for 18−25 SA. As we can see, in each of the 11-year cycles studied, there are 3 to 4 zigzags of GA fluctuations. The amplitude of changes in the QBV in the cycle depends on the phase of the SA and the observation cycle. For example, in 19SA and 23SA, the amplitudes of the QBV are almost the same and amount to ~1000 e14 J, but in 18SA, 21SA, 22SA, 24SA, 25SA the amplitudes of oscillations increase in the cycle with the QBV amplitudes at the maximum of the cycles and at their decline being several times larger than the QBV at the beginning and end of the cycle, and the maximum of the QBV occurs with a delay from the maximum of the SA, as we observe (see Fig. 2) in the GA as well. This pattern has an explanation, since after the maximum of the SA, the number of recurrent geomagnetic disturbances begins to increase, which leads to an increase in the GA. In addition, as shown in (Eher et al., 2012), we observe the maximum values of the solar wind speed in the phase of the SA decline. This phase of the SA is dominated by high-speed flows coming from coronal holes (Tsurutani et al., 1995). High-speed flows cause the growth of the southern component (B_z) of the interplanetary magnetic field and the stretching of the Parker helix, and hence lead to an increase in GA and an increase in the amplitudes of the QBV at the decline of SA. According to the aa- index, GA minima also lag behind the SA minima by a period of ~1 year (Kane, 2002; Hathway, 2010).

As shown in (Sumaruk & Sumaruk, 2009a), there is a clear dependence of recurrence on the sign of the SMF. The recurrence is minimal in years of changing the sign of the SMF, i.e., in years of large SA, and the maximum recurrence is in years of minimum solar activity. The peaks of recurrence were observed in 1976 and 1995. In these years, the SMF was positive. As we can see, the 22-year Hale cycle is clearly manifested.

Table 3, taken from (Petrovay, 2020), shows the 25SA forecasts - forecast method, years of minimum and maximum, maximum R_z value, and their authors (links in the original). As we can see, most authors predict a maximum SA in 2025±1 year.

5. Conclusions

Using the fact that the second tsug of the QBV variations in 25SA has not yet begun the figure shows a dashed line (see Fig. 3) and according to the above pattern, it should be larger in amplitude than the first tsug in 25SA; the number of recurrent geomagnetic disturbances should be high, since the solar SMF has a positive sign, and the 100-year SA cycle is on the growth branch; the energy entering the magnetosphere has now reached the maximum values of 24SA and continues to grow; analyzing table 3 on the 25SA maxima, it can be concluded that the maximum GA in 25SA will occur around 2026±1 year and will be comparable in magnitude to 23SA.

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