Long-term evolution of coronal holes on the Sun and occurrence frequencies of magnetic storms with gradual commencements

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Abstract. Long-term evolution of areas with open configuration of magnetic field (coronal holes) on the Sun reconstructed on the basis of H-alpha synoptic charts for the period 1887-2016 was studied and compared with annual occurrence frequencies of magnetic storms with gradual (GC) commencements. It was found that correlation between yearly values of coronal hole (CH) areas and sunspot numbers with no time shift is negative and not strong, but increases up to ∼0.6-0.7 when CH areas are delayed by 4-5 years relative to sunspot numbers. Temporal variations of CH areas in the Northern and Southern hemispheres are characterized by dominant ~11-year periodicities; however, they differ significantly on the multidecadal time scale. The wavelet spectra of CH areas in the Southern hemisphere, unlike those in the Northern one, reveal persistent periodicities of ~30-35 years on the studied time interval. Similar periodicities of ~30-35 years are observed in annual occurrences of GC magnetic storms which are caused by high-speed streams of solar wind from coronal holes. The results of cross wavelet analysis of annual occurrence frequencies of GC magnetic storms and areas of coronal holes revealed common periodicities ∼11, ∼35 and ∼60 years which confirmed a close link of these storms with the evolution of large-scale magnetic fields on the Sun.

1. Introduction

Coronal holes (CHs) are large-scale structures on the Sun arising in unipolar regions with the open configuration of magnetic field. They are observed as dark areas in extreme ultraviolet and soft X-ray ranges, as their temperature and density are less than in the surrounding coronal areas (e.g., [1]). The open configuration of magnetic field lines allows particles to escape more readily into interplanetary space which leads to the formation of high-speed streams of solar wind. The high-speed streams of solar wind, along with coronal mass ejections (CMEs), are responsible for disturbances of the Earth’s magnetic field (e.g., [2]). As coronal holes are long-living structures which can exist during several rotations of the Sun, they cause recurrent streams of high-speed solar wind. The interaction between high-speed streams and slow solar wind results in the formation of co-rotating interaction regions (CIRs) with compressed magnetic field, which cause magnetic storms with gradual (GC) commencements [3]. GC magnetic storms develop gradually and, unlike storms with sudden commencements, which are usually associated with CMEs, no sudden increase of the Earth’s magnetic
field is observed before the main phase of a GC storm. Occurrence of high-speed solar wind streams from coronal holes increases in a declining phase of the 11-year solar cycle, so their contribution to geomagnetic activity also increases. It was found [4] that annual occurrences of magnetic storms with gradual commencements are characterized by a pronounced variability on the multidecadal time scale. Thus, the aim of this work is to study long-term variations in the evolution of coronal holes which are sources of high-speed solar wind streams, as well as to compare these variations with those in annual occurrences of magnetic storms with gradual commencements.

2. Variations of coronal hole areas in the Northern and Southern hemispheres

As experimental data for this study, we used areas with the open configuration of magnetic field (coronal holes) reconstructed on the basis of H-alpha synoptic charts for 1887-2016 according to the method [5]. Large-scale H-alpha structure of the chromosphere (location of prominences observed as dark filaments) is known to show rather accurately neutral lines of large-scale magnetic fields on the Sun [6]. So, H-alpha charts allow investigating the evolution of these fields during those solar activity cycles when no magnetographic observations were carried out. The method of the reconstruction of open magnetic flux areas is described in details in [7].

Figure 1a presents temporal variations of mean yearly values of reconstructed CH areas in the Northern and Southern hemispheres compared with those of sunspot numbers SSN [8]. One can see that variations of CH areas are rather similar in both hemispheres, with maximal values being observed in a declining phase of the 11-year solar cycles close to their minima; however, some differences can be noted. Indeed, the data in figure 1b show no strong links between CH areas in the Northern and Southern hemispheres, the correlation coefficients amounting only 0.54.

![Figure 1](image.png)

**Figure 1.** a) Temporal variations of yearly values of reconstructed CH areas in the Northern (NH) and Southern (SH) hemispheres. Sunspot numbers SSN are shown with gray bar chart. b) CH areas in the Southern hemisphere versus those in the Northern one.

The correlation coefficients between yearly values of CH areas and sunspot numbers are given in table 1 for different time delays of CH areas relative to SSN, with statistical significance of the coefficients being estimated on the basis of Monte-Carlo simulations. It is seen that with no time delay the correlation coefficients between the studied values are negative, but the absolute values do not exceed ~0.5 and the confidence level P (indicated in italics in brackets) is less than 0.9. The correlations reach maxima (~0.6−0.7, P ≥ 0.985) when CH areas are delayed by 4-5 years relative to SSN. It should be noted that the correlations turn out to be somewhat higher, if SSN are delayed relative to CH areas. With a time delay of SSN by 6 years (i.e., CH areas are taken for the previous solar cycle) the correlation coefficients reach 0.698 for CH areas of the Northern hemisphere and 0.724 for total CH areas, with the confidence level P ≥ 0.999. Statistically significant correlations between CH areas and sunspot numbers suggest that coronal holes (large-scale magnetic fields on the
Sun) and sunspots (manifestation of local magnetic fields) are interconnected and form a single global complex of magnetic activity, which is in agreement with the suggestions in [1].

| Time delay, yrs | Northern hemisphere | Southern hemisphere | Total     |
|----------------|---------------------|---------------------|-----------|
| 0              | −0.504 (0.874)      | −0.330 (0.866)      | −0.475 (0.882) |
| +4             | 0.597 (0.985)       | 0.586 (0.997)       | 0.674 (0.998) |
| +5             | 0.610 (0.992)       | 0.528 (0.989)       | 0.648 (0.996) |

Let us consider spectral features of CH area variations. Figure 2 shows the wavelet spectra (basis Morlet) of yearly values of reconstructed CH areas after the removal of polynomial trends of the 2nd order. The spectra were normalized by variance which allows comparing different wavelet spectra and assessing significance. One can see that the spectra of CH areas in both hemispheres are characterized by pronounced ∼11-year periodicities; however, they differ noticeably on the multidecadal time scale. The wavelet spectra of CH areas in the Southern hemisphere, unlike those in the Northern one, reveal persistent periodicities ∼30-35 years. Multidecadal periodicities are likely to exist also in the Northern hemisphere, but they seem to be weakened in ∼1920-1980, whereas in the Southern hemisphere they were enhanced. The obtained results provide evidence for the north-south (N-S) asymmetry in the evolution of large-scale magnetic fields on the Sun on the multidecadal time scale.

![Wavelet Spectra](image1)

**Figure 2.** Local and global wavelet spectra (basis Morlet) of yearly values of reconstructed CH areas in the Northern (left) and Southern (right) hemispheres after the removal of the 2nd order polynomial trends. The spectra were normalized by variance.

The N-S asymmetry is a characteristic feature of solar activity, which is observed in different solar indices from the photosphere to the corona, with the origin of this asymmetry remaining unclear. It
indicates that physical processes on the Sun develop not quite similarly in the Northern and Southern hemispheres: one of them is more active for some time period and then vice versa. The N-S asymmetry is observed on time scales of several months and longer, including a multidecadal time scale [1]. So, we can suggest that in the 20th century some processes contributing to multidecadal variations in CH development could have been stronger in the Southern hemisphere.

3. Annual occurrences of magnetic storms with gradual commencements and their links to coronal hole evolution

As coronal holes reach maximal development in a declining phase and minima of the 11-year solar cycles, high-speed solar wind streams from them become the main contributor to geomagnetic activity in this period. Unlike CMEs, which are usually responsible for magnetic storms with sudden commencements, high-speed streams of solar wind cause magnetic storms with gradual commencements. Let us compare temporal variations of coronal hole areas and those of annual frequency of occurrence of GC magnetic storms.

For the study we used the data of magnetic observatories IZMIRAN (55°45′N, 37°37′E; geomagnetic latitude Φ~51°) [9] and Slutsk/Pavlovsk (SPb Branch of IZMIRAN, 59°57′N, 30°42′E; Φ~58°) [10]. The combined time series of annual frequency of occurrence of GC magnetic storms (number of events during a year) was constructed, the data from Slutsk/Pavlovsk for 1878-1933 and IZMIRAN for 1934-2015 being used. This series includes magnetic storms of different intensities (moderate, strong and very strong). Temporal variations of annual frequency of occurrence of these storms are presented in figure 3 and compared with sunspot numbers. One can see that annual occurrences of GC storms with intensities from moderate to very strong increase in the maximum of a secular cycle in the mid-20th century, but do not follow 11-year variations of SSN.

3. Annual frequencies of occurrence (number of events during a year) of GC magnetic storms. Sunspot numbers SSN are shown with gray bar chart. Dashed line shows the 2nd order polynomial trend.

Figure 4 shows the wavelet spectra of annual occurrence frequencies of GC magnetic storms after the removal of the 2nd order polynomial trend, the spectra being normalized by variance. One can see that, along with 11-year variations, these spectra reveal well pronounced variations on the multidecadal time scale with the maxima at ~35 and ~60 years. The ~35-year periodicities in the spectra of GC storm occurrences, which are persistent on the entire time interval under study, are close to those observed in the spectra of CH areas of the Southern hemisphere. Let us note that periodicities of ~30-35 years are observed in a number of meteorological and geophysical characteristics and correspond to the well-known climatic Brückner cycle [11].

Cross wavelet spectra of GC storm occurrences and reconstructed CH areas in different hemispheres are presented in figure 5. The spectra reveal common periodicities of ~11 and ~60 years in GC storm occurrences and Northern hemisphere CH areas, as well as ~11, ~35 and ~60 years in GC storm occurrences and Southern hemisphere CH areas. Figure 6 shows cross wavelet spectra of GC storm occurrences and total CH areas on the Sun. These cross spectra reveal three common periodicities in the studied values: ~11, ~35 and ~60 years. Thus, the data in figures 5 and 6 provide

Figure 5. Cross wavelet spectra of GC storm occurrences and CH areas in different hemispheres.
evidence for a noticeable contribution of coronal holes of both hemispheres in the formation of ~11-year periodicities in GC storm occurrences. At the time, coronal holes of the Southern hemisphere seem to be the main reason for ~30-35-year periodicities observed in GC storm occurrences, whereas those of the Northern hemisphere contributes to a greater extent to ~60-year periodicities. The results obtained show that, on the whole, the main periodicities in occurrence of magnetic storms with gradual commencements are closely associated with long-term variations in characteristics of coronal holes, i.e. the evolution of large-scale magnetic field on the Sun.

**Figure 4.** Local and global wavelet spectra (basis Morlet) of annual frequencies of occurrence of GC magnetic storms after the removal of the 2nd order polynomial trend. The spectra were normalized by variance.

**Figure 5.** Local and global cross wavelet spectra (basis Morlet) of annual occurrence frequencies of GC storms and yearly values of reconstructed CH areas in the Northern (left) and Southern (right) hemispheres after the removal of the 2nd order polynomial trends. The spectra were normalized by variance.
4. Conclusions
The results of the study showed that temporal variations of reconstructed areas of coronal holes both in the Northern and Southern hemispheres are characterized by dominant ∼11-year periodicities, but differ noticeably on the multidecadal time scale. The wavelet spectra of coronal hole areas in the Southern hemisphere, unlike those of the Northern one, reveal strong periodicities of ∼30-35 years which are observed in annual occurrences of magnetic storms with gradual commencements. Cross wavelet analysis of annual occurrences of magnetic storms with gradual commencements and areas of coronal holes showed common periodicities of ∼11, ∼35 and ∼60 years, which indicates a close link of these storms with the evolution of large-scale magnetic fields on the Sun.

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Figure 6. The same as in figure 5, but for total CH areas.