Section 6. Miscellaneous

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Contributed papers

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Dynamics of Solar and Stellar Convection Zones and Atmospheres
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Features of the solar minimum 24/25 in the evolution of polar and non-polar coronal holes

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Abstract. We present a study of the evolution of two types of coronal holes (CHs) in the solar minimum of 24/25, which was preceded by a prolonged minimum of 23/24 and a weak 24 solar cycle. The goal of the study is to clarify whether the behavior of CHs during this period is also unusual? The study is based on the material of observations obtained by SDO/AIA/193. The Heliophysics Events Knowledgebase was used to localize the CHs and calculate their areas. Analysis of the evolution of the areas of polar and non-polar CHs in solar minimum 24/25 revealed a number of features. The hemispheric asymmetry is evident both in solar activity indices and in the localization of maxima of polar and non-polar CH areas. The hemispheric area imbalance is minimal for polar CHs and pronounced in the regions of non-polar CHs and sunspots. This is consistent with the general concept of polar CHs as the main source of the Sun's dipole magnetic field. The areas of polar CHs significantly exceed the areas of non-polar CHs and make a significant contribution to the total area of all CHs in the solar disk. It is concluded that the dynamics of polar and nonpolar CHs suggests that the 24/25 minimum is rather close to earlier minima than to the 23/24 minimum.

Keywords. Solar Cycle, Solar minimum, Solar Corona, Coronal hole, Evolution of Coronal holes

1. Introduction

The structure of the corona is quite complex and dynamic and depends both on the spatial distribution of solar formations on its surface and on the phase of the solar cycle. During the period of activity minimum, open-field regions above the poles (polar coronal holes) reach their maximum expansion, and the number of low-latitude regions of closed strong field (active regions and sunspots) is minimal. The dipole structure of the global magnetic field in this time is very prominent and there are no significant inclusions of open flux in the equatorial zone Abramenko *et al.* (2010). Typical structure corona in the solar minimum is shown in Fig. 1.

Coronal holes (CHs) are areas of open magnetic configuration on the Sun: a structure in which magnetic lines of force freely extend into interplanetary space and are closed at infinity. These areas are characterized by much lower temperatures and lower densities compared to their surroundings, which make CHs, appear dark. The evolution of CHs is closely related to the evolution of the large-scale solar magnetic fields. CHs are a reaction of global internal processes in the Sun. Therefore, CHs are an integral part of the solar activity (SA) cycle. By analyzing the dynamics of CHs, in particular, their areas, we can judge the dynamics of the Sun and the progress of the cycle.

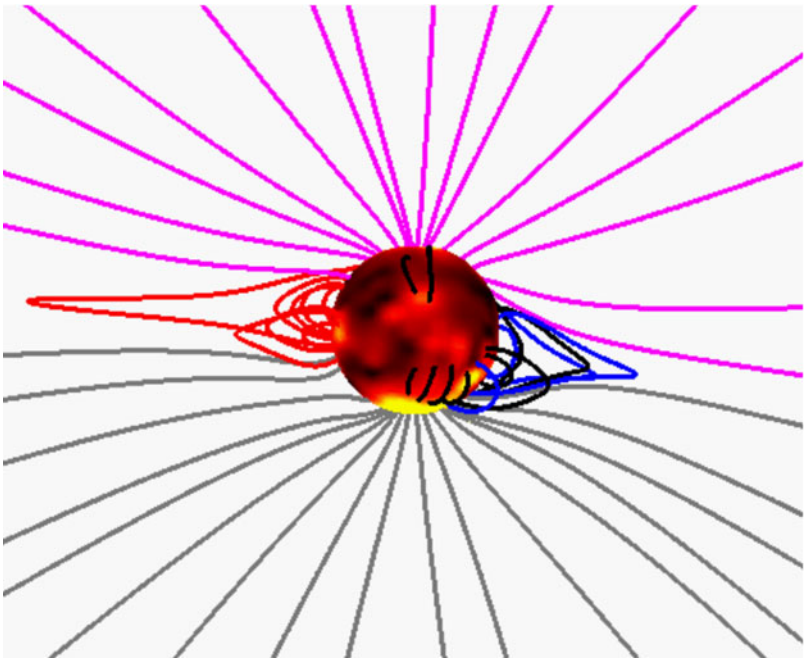

Figure 1. Typical structure corona in the solar minimum.

1.1. *The solar activity cycle 24 and minimum 24/25*

The solar activity cycle 24 (Fig. 2(a)) that recently ended was one of the weakest cycles for the last 100 years of observations (Fig. 2(b)).

It differed from the previous cycles in a number of parameters. Cycle 24 is known to have a lower maximum and less flare activity than the previous cycles. This cycle exhibited a relatively large N–S asymmetry of the polar field inversion: the sign of the field at the north pole changed more than a year earlier than at the south pole. The cycle also had a strong asymmetry of the hemispheres in many other parameters. It should be said, solar minimum 23/24 exhibits features that differ notably from features commonly seen in minimum 22/23 and earlier ones. The polar CHs were less dominant than those in previous solar minima, but the low-latitude CHs, which are not commonly seen during previous solar minima, were relatively large and persist many rotations Abramenko *et al.* (2010). Since the 24th solar cycle and the minimum preceding it had of a special character, the questions naturally arises:Is the 24/25 solar minimum (Fig. 2(a)) also unusual? This question motivates scientists to investigate this minimum in more detail. Thus, the authors of Huichao Li *et al.* (2021) considered the evolution of the sunspot number and polar field strength, compared the 24/25 minimum with the two previous minima 22/23 and 23/24 and showed:

– Minima 24/25 and 23/24 showing lower activity level than minimum 22/23. But to the end of 2020 SSN raises harply for minimum 24/25.

– The polar field strength of minimum 24/25 is stronger than that during minimum 23/24 in average, but still weaker than minimum 22/23.

– The N–S asymmetry of the polar field is more evident during minimum 24/25 than during minimum 23/24. A similar north–south asymmetry is found during minimum 22/23.

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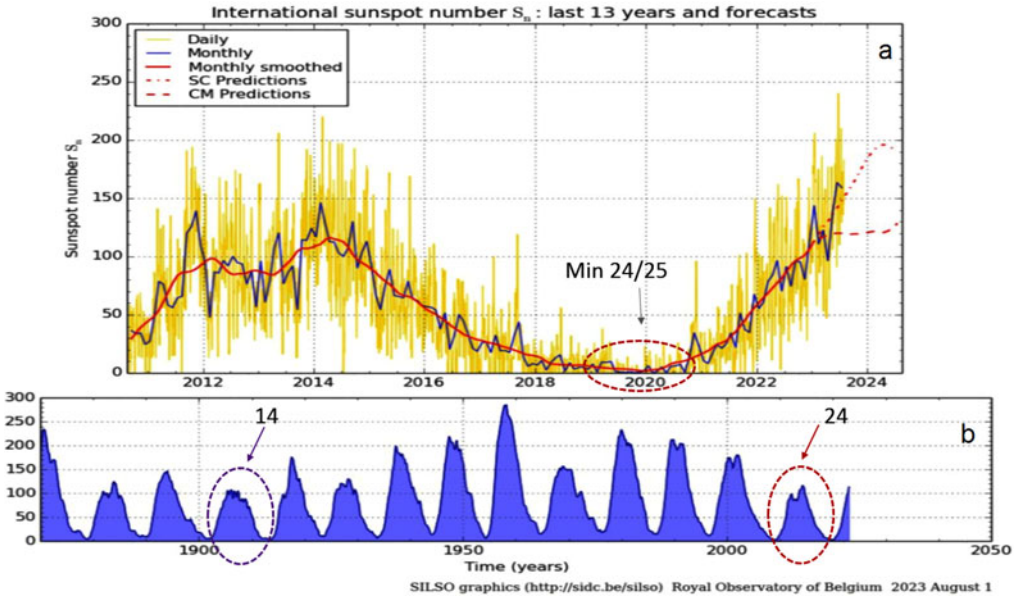

Figure 2. Daily and monthly sunspot number (last 13 years – a). Monthly 13-month smoothed sunspot number (blue) from 1870 up to the present – b.

2. Evolution two type of coronal holes during the minimum 24/25

The evolution of CHs on the scale of the solar cycle was studied earlier Andreeva (2023). Variations of the daily total area were obtained for the entire visible surface of the solar disk, separately for both hemispheres and for 2 types of coronal holes (Fig. 3(b), (c-d) and (e-f)). The asymmetry of the hemispheres in the distribution of sunspot areas and two types of coronal holes was revealed (Fig. 4(a) and (b-c)).

Here, as in our earlier works Andreeva & Malashchuk (2020), Andreeva *et al.* (2020), Andreeva *et al.* (2021), Andreeva (2023), we define as polar (CHs_pol) the CHs that begin in the polar regions, i.e., from latitude 90°, and extend to lower latitudes depending on their development and cycle phase, sometimes to middle and even low latitudes (Fig. 5 SPoCA 23027, 23064, 23632, 23717). Non-polar (CHs_nonpol) are isolated CHs, not connected with the pole. Most often, these are mid- and low-latitude CHs, but sometimes CHs_nonpol appear at relatively high latitudes (Fig. 5 SPoCA 23097, 23715, 23716).

In addition, we adopt that the area of a CH crossing the equator is divided into two parts, and each of them refers to the corresponding hemisphere, depending on its location. The contribution of such CHs is quite small because their number is less than 7% of the total number of CHs.

In this paper, we extract from the previously obtained series the interval corresponding to the 24/25 minimum (Fig. 3), analyze and evaluate the contribution of polar and nonpolar coronal holes to the evolution and hemispheric asymmetry of large-scale solar activity during this period (Fig. 6). We want, at least partially, to answer the question posed earlier: "Is the 24/25 minimum special in terms of CHs evolution?". To analyze the nature of the solar minimum, usually choose a period of time around the absolute minimum (in our case it is December 2019), when solar activity is consistently low. As can be seen in Fig. 2(a), the sunspot activity level is low in the 2-year period around the absolute minimum of solar cycle 24, so we choose the period from 01.12.2018 to

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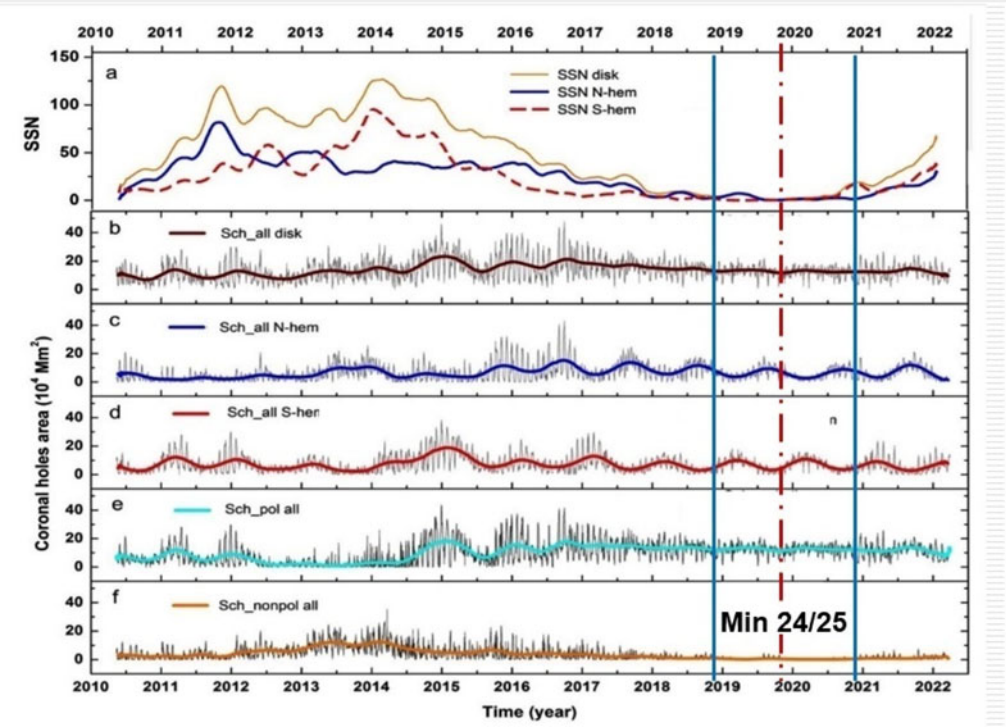

Figure 3. Variations of the SSN and daily total CH areas in 2010-2022.

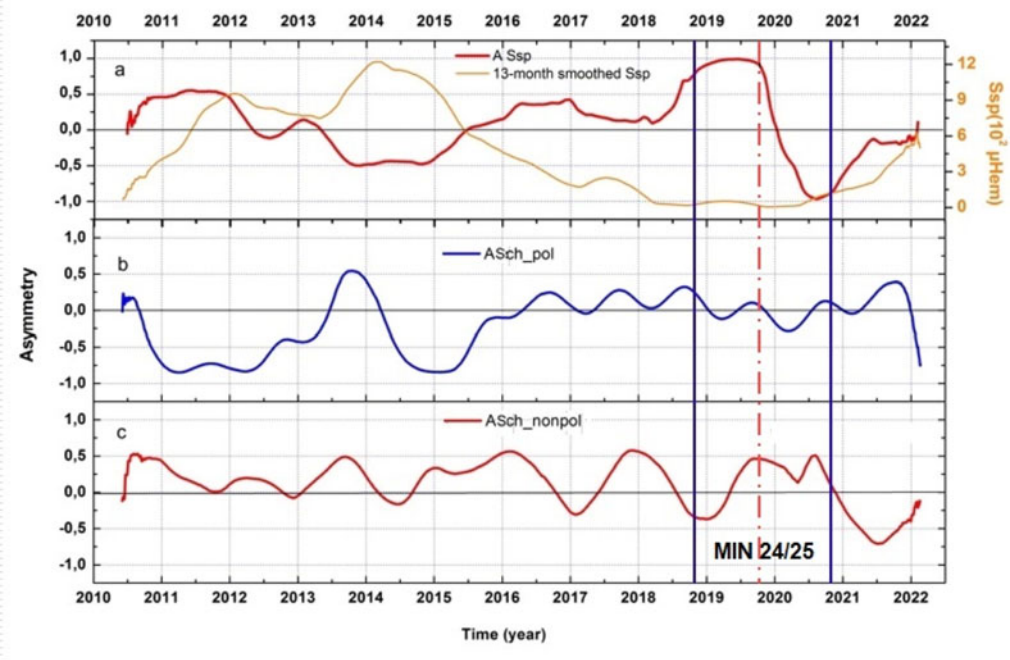

Figure 4. N-S asymmetry of the areas of sunspots and coronal holes in 2010-2022.

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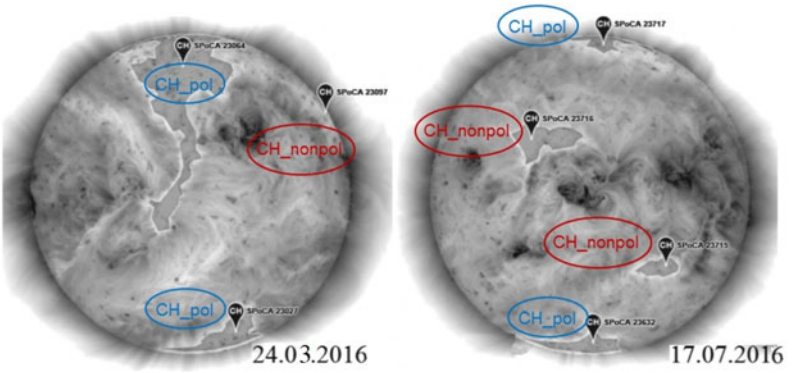

Figure 5. Inverted images of the Sun obtained by SDO/AIA in the Fe XII 19.3 nm line. The regions on the solar disk marked "CH" are coronal holes extracted from the EUV image with the SPoCA method.

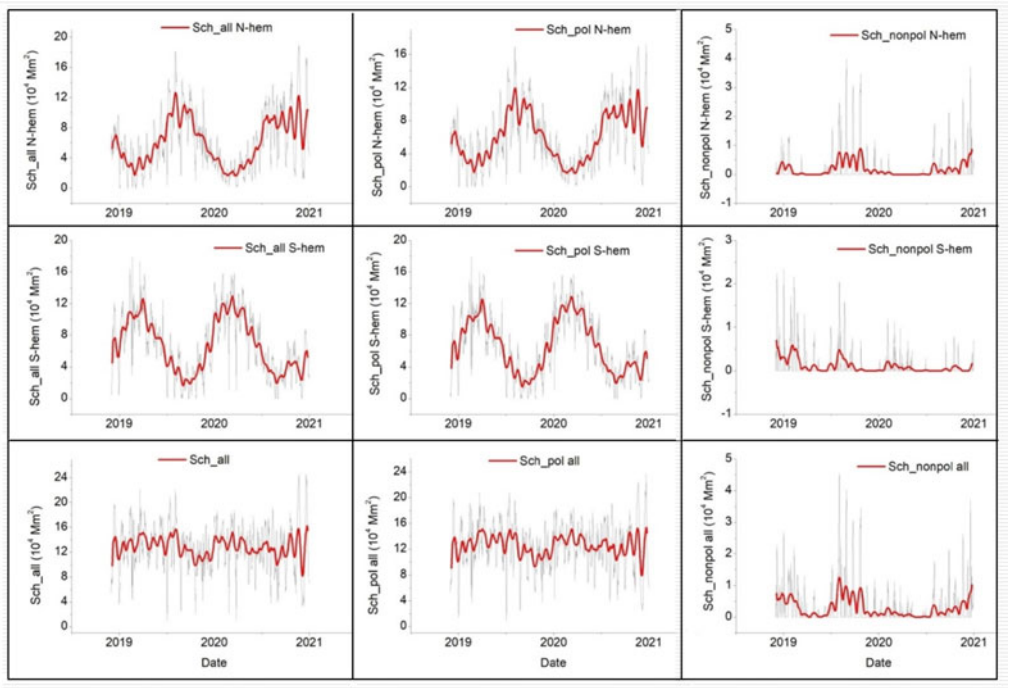

Figure 6. Evolution of polar and non-polar coronal holes during the minimum 24/25.

31.12.2020 to analyze the 24/25 minimum. The SSN data are obtained from the sunspot index and long-term solar observations (SILSO).

Figure 6 shows the dynamics of the daily areas of all, polar and nonpolar CHs (columns from left to right) observed in the N and S hemispheres and on the entire visible surface of the solar disk (rows from top to bottom) at the 24/25 minimum. There is an obvious difference in the operation of the hemispheres in generating both polar and non-polar coronal holes. At the beginning of the minimum, the southern hemisphere leads in the generation of non-polar coronal holes, while before and after the absolute minimum, the northern hemisphere leads. For polar CHs, the asymmetry in amplitude is less pronounced. We observe hemispheric asymmetry in the time of appearance of the maximum

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peak areas for both groups. It can be seen that polar CHs make a significant contribution to the total area of all CHs.

3. Conclusions

Analysis of the evolution of the areas of polar and non-polar coronal holes in the solar minimum 24/25 revealed a number of features:

– Hemispheric asymmetry is manifested both in the indices of solar activity and in the localization of the maximum regions of polar and non-polar coronal holes.

– The area imbalance of the hemispheres is minimal for polar coronal holes and is pronounced in the areas of non-polar coronal holes and sunspots. This is consistent with the general concept of polar coronal holes as the main source of the sun's dipole magnetic field.

– The areas of polar coronal holes are significantly larger than the areas of non-polar ones and make a significant contribution to the total area of all coronal holes on the Sun's disk.

The total area of polar coronal holes approached the average level of values of about $(12.5 \pm 0.8) \times 10^4 Mm^2$. While the area of all non-polar coronal holes is only about $0.5 \times 10^4 Mm^2$.

Of course, the concept of "unusual solar minimum" is multifaceted, but as far as the evolution of two types of coronal holes is concerned, minimum 24/25 was similar to earlier minima, in contrast to the 23/24 minimum.

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