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SOLAR WIND PARAMETERS IN RISING PHASE OF SOLAR CYCLE 25: SIMILARITIES AND DIFFERENCES WITH SOLAR CYCLES 23 AND 24

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Abstract. Solar activity and solar wind parameters decreased significantly in solar cycles (SCs) 23–24. In this paper, we analyze solar wind measurements at the rising phase of SC 25 and compare them with similar data from the previous cycles. For this purpose, we simultaneously selected the OMNI database data for 1976–2022, both by phases of the 11-year solar cycle and by large-scale solar wind types (in accordance with catalog [http://www.iki.rssi.ru/pub/omni]), and calculated the mean values of the plasma and magnetic field parameters for the selected datasets. The obtained results support the hypothesis that the continuation of this cycle will be similar to that of cycle 24, i.e. SC 25 will be weaker than SCs 21 and 22.

Keywords: solar wind, solar cycle.

INTRODUCTION

The solar wind (SW), formed by the expansion of the hot solar corona into the interplanetary medium, is one of the main subjects of space research. On the one hand, the study of the solar wind provides further insight into properties of the solar atmosphere and the processes of plasma outflow from it [Hundhausen, 1972; Schwenn, 2006, 2007]. On the other hand, the solar wind is the main agent that carries disturbances from the Sun to Earth and causes space weather effects [Gonzalez et al., 1999; Yermolaev et al., 2005; Temmer, 2021].

Direct measurements of the solar wind began at the beginning of the space age [Gringauz, 1961; Neugebauer, Snyder, 1962] and cover cycles 20–25 (see, for example, the solar wind measurement database [https://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni; King, Papitashvili, 2005]). The measurements started during the epoch of high solar activity; and at the minimum between SCs 22 and 23, solar activity began to decrease and continued to do so in SCs 23 and 24 [Feynman, Ruzmaikin, 2011; Zolotova, Ponyavin, 2014; Biswas et al., 2023]. This solar activity decrease can have a significant effect on Earth. According to approximation of sunspot numbers in the maxima of the last 20 solar cycles by secular Gleissberg cycles, current SC 25 may be lower than the Grand Minimum, i.e. solar activity can decrease to the level of the Dalton Minimum (see Figure 4 of the review [Petrovay, 2020]). The decrease in solar activity was accompanied by a number of significant changes in the solar wind, which led to changes in Earth's magnetosphere [McComas et al., 2013; Gopalswamy et al., 2015; Yermolaev et al., 2021a, b, 2022a, b; Mursula et al., 2022]: 1) changes in the structure of the heliosphere, such as a decrease in the number of coronal mass ejections (CMEs) and their manifestations in the interplanetary medium with an almost constant number of high-speed streams from coronal holes and associated corotating interaction regions; 2) a decrease in solar wind parameters both in solar wind streams of different types and in different solar cycle phases; 3) a decrease in magnetospheric disturbances, specifically an almost tenfold decrease in the number of geomagnetic storms.

The Sun has passed the rising phase of SC 25 (see the behavior of the annual average sunspots between 2019 and 2022 in Figure 1), and direct measurements of the solar wind at this phase are currently available for research. Together with solar observations, analysis of these measurements makes it possible to verify models predicting the development of the current solar cycle, and, in particular, to obtain more reliable forecasts of the

Sun's behavior, the heliosphere, and space weather effects near solar maximum [Javaraiah, 2017; Chowdhury et al., 2022; Lamy, Gilardy, 2022; Du, 2023].

In our previous article [Yermolaev et al., 2021a], we have analyzed how the average parameters changed in various large-scale solar wind streams at different phases of SCs 21–24 (1976–2019). To do this, we selected data from the OMNI database [King, Papitashvili, 2005], both by solar cycle phases and by large-scale solar wind types [Yermolaev et al., 2009], and calculated average parameters for the selected data sets. We have found that in SCs 23 and 24 (1997–2019) during the corresponding solar cycle phases in solar wind streams of all types the parameters decreased by 20–40 % compared to SCs 21 and 22. In this paper, using a similar data set, we first compare the rising phase of SC 25 with similar phases of four previous SCs to determine similarities and differences between the current and previous SCs and predict the development of SC 25.

1. DATA AND METHODS

We use the same sources of information as in our previous work [Yermolaev et al., 2021a]: 1) hourly average data on solar wind measurements for 1976–2022 from the OMNI database [https://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni; King, Papitashvili, 2005]; 2) intervals of different SW types from the catalog of large-scale phenomena since 1976 [http://www.iki.rssi.ru/pub/omni; Yermolaev et al., 2009], created on the basis of OMNI data.

According to the catalog, the following large-scale (>10^6 km) SW types have been identified:

- *Quasi-stationary types:* 1) Heliospheric Current Sheet (HCS); 2) slow flows streams from coronal streamers (Slow); 3) fast streams from coronal holes (Fast).
- *Disturbed types:* 4) compression regions between slow and fast SW stream types — Corotating Interaction Regions (CIRs); 5) compression regions (Sheath) between slow SW stream type and fast interplanetary manifestations of CME (Interplanetary Coronal Mass Ejection, ICME); 6, 7) two variants of ICME: Ejecta and magnetic cloud (MC), MC differs from Ejecta by a higher and more regular interplanetary magnetic field (IMF).

The classification we use is generally accepted (for details, see [Yermolaev et al., 2021a]); the SW type identification method is described in detail in [Yermolaev et al., 2009].

The entire time interval 1976–2022 has been divided into 18 subintervals corresponding to phases of SCs 21–25 (see Figure 1 and Table 1). Unlike previous works [Yermolaev et al., 2021a, b], in this work, the minimum phase between SCs 24 and 25 spans 2017–2020, and we have also added the period 2021–2022 corresponding to the rising phase. We have averaged data in each of the eighteen subintervals and for each of the eight SW types (the seven listed above plus their sum). All parameters in the averaging intervals have a large statistical spread, and their standard deviation is close to the average value. However, due to the large (~10^3) number of points in the averaging sets for all SW types (except MC, where statistics is small [Yermolaev et al., 2021a]), the statistical error (i.e. the standard deviation divided by the square root of the number of measurement points) appeared to be small, and the trends in behavior of these parameters is of sufficient statistical significance [Bendat, Piersol, 1971]. Typical values of standard deviations and statistical errors in plasma and magnetic field parameters for the data sets under study are listed in Tables in our articles [Yermolaev et al., 2021a, b]. Note that the greatest spread of the values is observed for the proton temperature T, and, since it has a lognormal distribution [Burlaga, Lazarus, 2000; Dmitriev et al., 2009], we averaged the lg$T$ value.

2. RESULTS

Figures 2–7 exhibit time profiles of the solar wind plasma and interplanetary magnetic field parameters averaged over solar cycle phases (see Table 1): minimum — black circles; rising phase — blue triangles; maximum — purple squares; declining phase — green upside triangles; without phase separation (SC average) — red squares. The rightmost blue triangles in all panels indicate the rising phase of SC 25, and these values represent the main result of this work. Data for magnetic clouds are widely scattered in all Figures due to the small number of events.

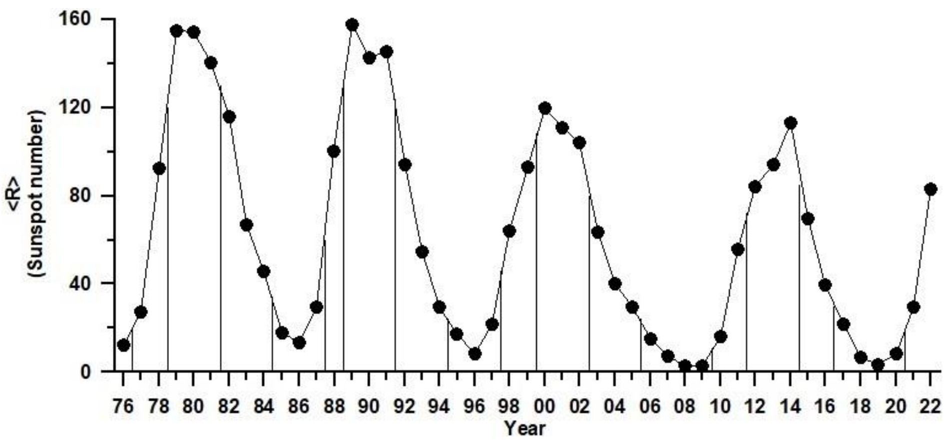

Figure 1. Annual number of sunspots *R*. Numbers and vertical lines show the phase distribution for solar cycles 21–25

Table 1

Phase averaging intervals for solar cycles 21–25

Subinterval number	Solar cycle number	Solar cycle phase	Years
1	21	minimum	1976
2		rising	1977, 1978
3		maximum	1979–1981
4		declining	1982–1984
5		minimum	1985–1987
6	22	rising	1988
7		maximum	1989–1991
8		declining	1992–1994
9		minimum	1995–1997
10	23	rising	1998–1999
11		maximum	2000–2002
12		declining	2003–2005
13		minimum	2006–2009
14	24	rising	2010, 2011
15		maximum	2012–2014
16		declining	2015–2016
17		minimum	2017–2020
18	25	rising	2021–2022

We start the analysis with the solar wind bulk velocity, which, as shown in [Yermolaev et al., 2021a], turned out to be least affected by the weakening of solar activity in SCs 23–24. Figure 2 shows that the solar wind velocity is quite stable and weakly depends both on SC phase and number and on SW type. The only short-term increase in the average velocity was observed during the CME-driven events (Sheath, Ejecta, and MC) in the declining phase of SC 23; it is associated with a short-term increase in solar activity (in particular, extreme events in October and November 2003 and 2004). The deviation of the average SW velocity during the rising phase of SC 25 from that during the previous minimum phase for different SW types is less than 20 km/s; it is noticeably lower than the standard deviations and corresponds to the velocity behavior at the beginning of SC 24. Thus, no specific features are observed in the rising phase of SC 25 compared to that of SC 24.

Figure 3 illustrates variations in the proton temperature logarithm lg*T*. Despite the wide temperature spread, the profiles averaged over solar cycle phases on a logarithmic scale are rather smooth with a clear tendency for the temperature to be higher during the maximum and declining phases of SC 22–24 than during the minimum and rising phases: in most cases, the lines for the maximum and declining phases are located above the rest of the lines.

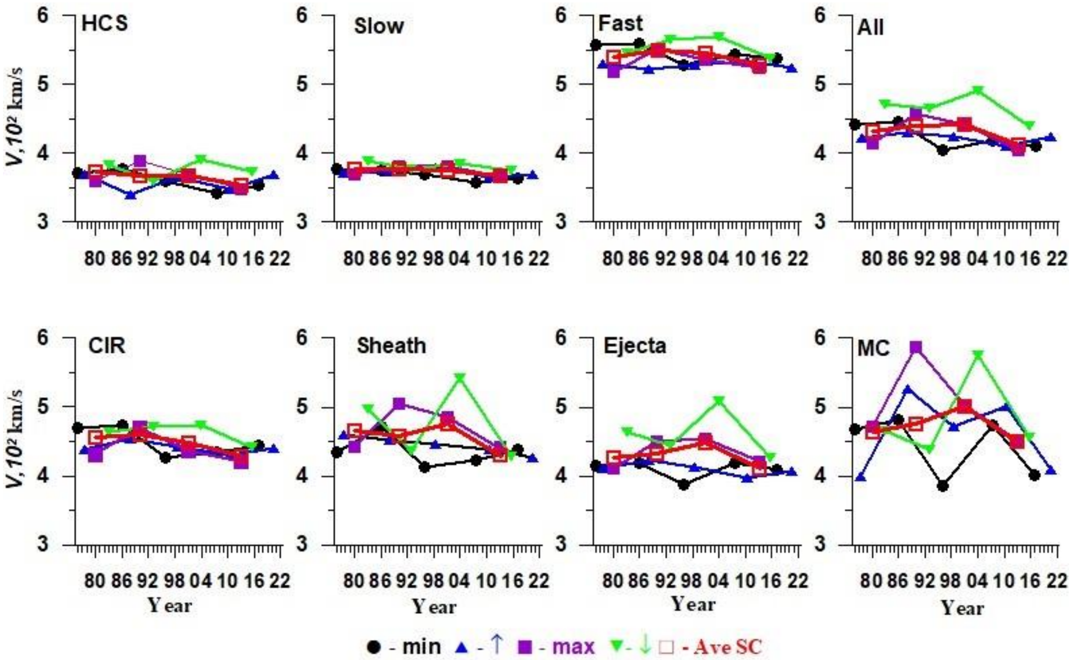

Figure 2. Time profiles of bulk speed *V* in seven SW types (HCS, Slow, Fast, CIR, Sheath, Ejecta, and MC) and without SW type selection (All)

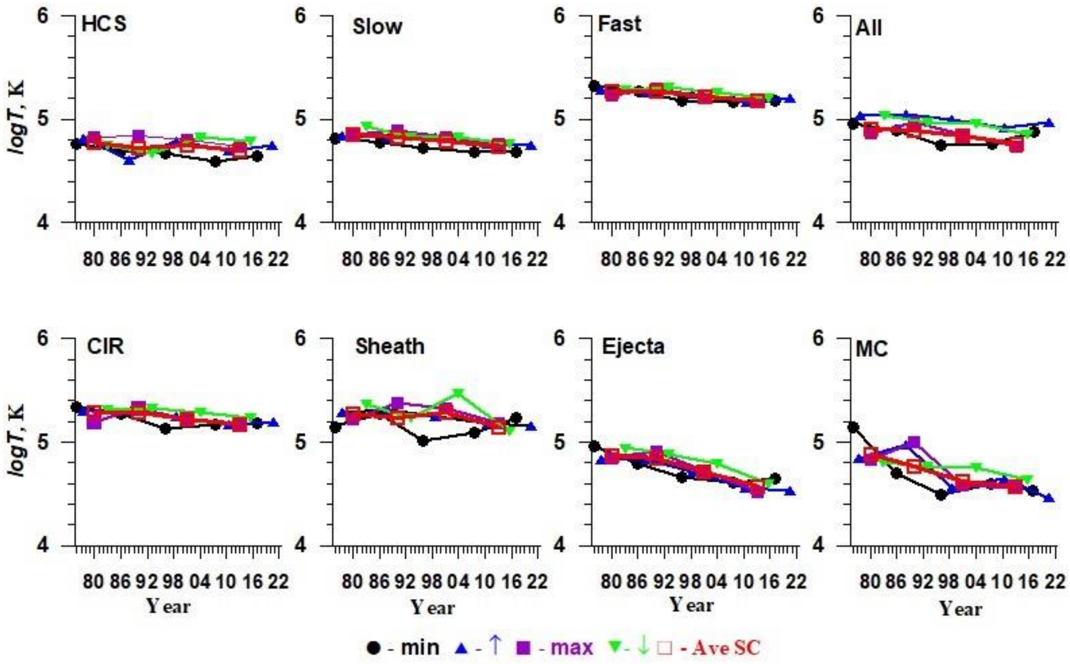

Figure 3. Time profiles of proton temperature *T* logarithm

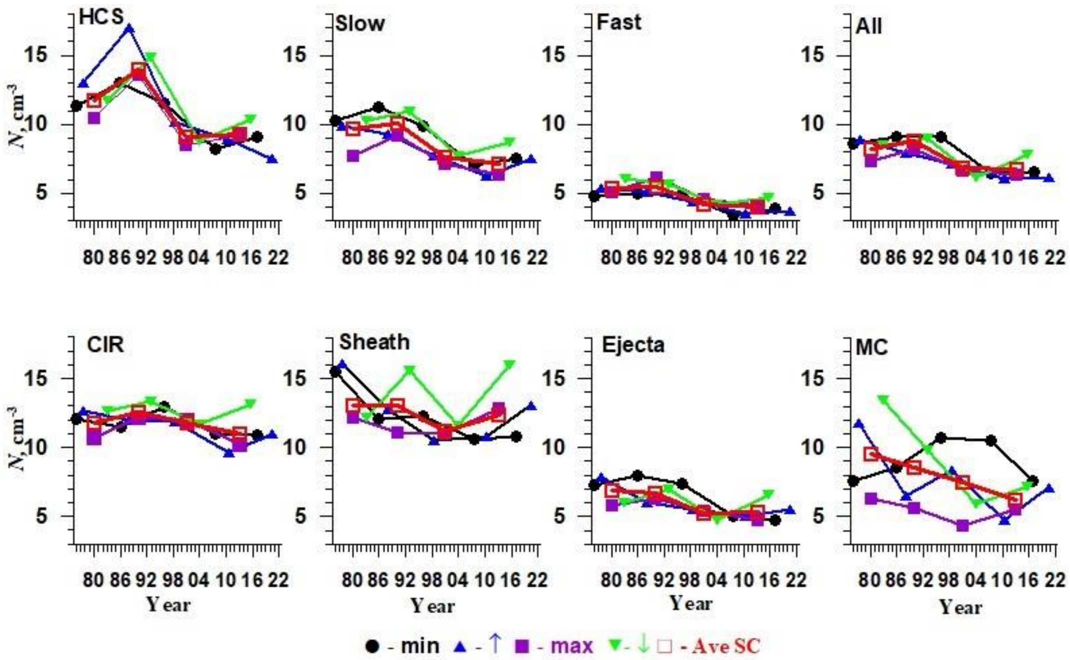

Figure 4. Time profiles of density *N*

It can be noted that the tendency for *T* to increase during the rising phase of SC 25 is observed only for quasi-stationary SW types (HCS, Slow, and Fast) and is not observed for disturbed SW types (CIR, Sheath, Ejecta, and MC). Since the number of disturbed SW types is small during this period (see, e.g., [Yermolaev et al., 2023]), the *T* behavior for the sum of all types (All) is similar to the behavior for quasi-stationary SW types.

Figure 4 shows variations in the density *N*. Despite the wide spread of values (slightly smaller than the temperature spread), the *N* curves for quasi-stationary SW types are quite smooth and show a tendency toward higher values during the minimum and declining phases. The density after the minimum between SCs 22 and 23 decreases markedly in all SC phases and for all SW types (with small statistics and a wide spread of MC data, this density decrease is seen when it is averaged over the full cycle duration (red squares in the panel for MC)). The density dynamics during the transition from the minimum phase to the rising phase of SC 25 is similar to the dynamics during the corresponding period of SC 24.

Time profiles of the interplanetary magnetic field magnitude *B* are presented in Figure 5. For different SW types, the curves show higher *B* for the maximum and declining phases, and after minimum between SCs 22 and

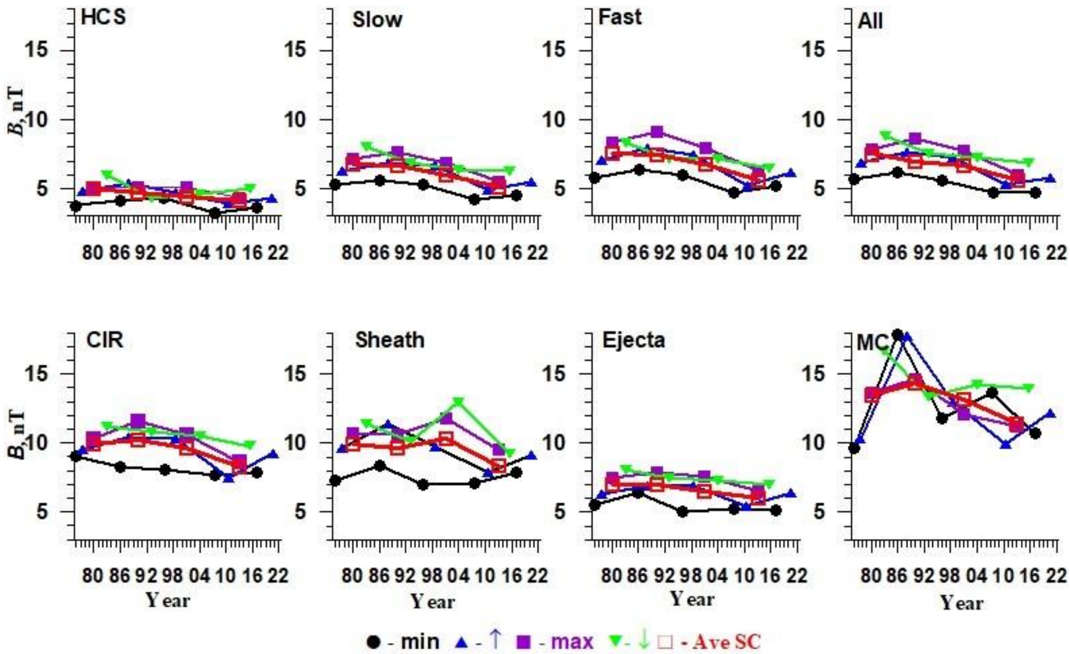

Figure 5. Time profiles of IMF *B*

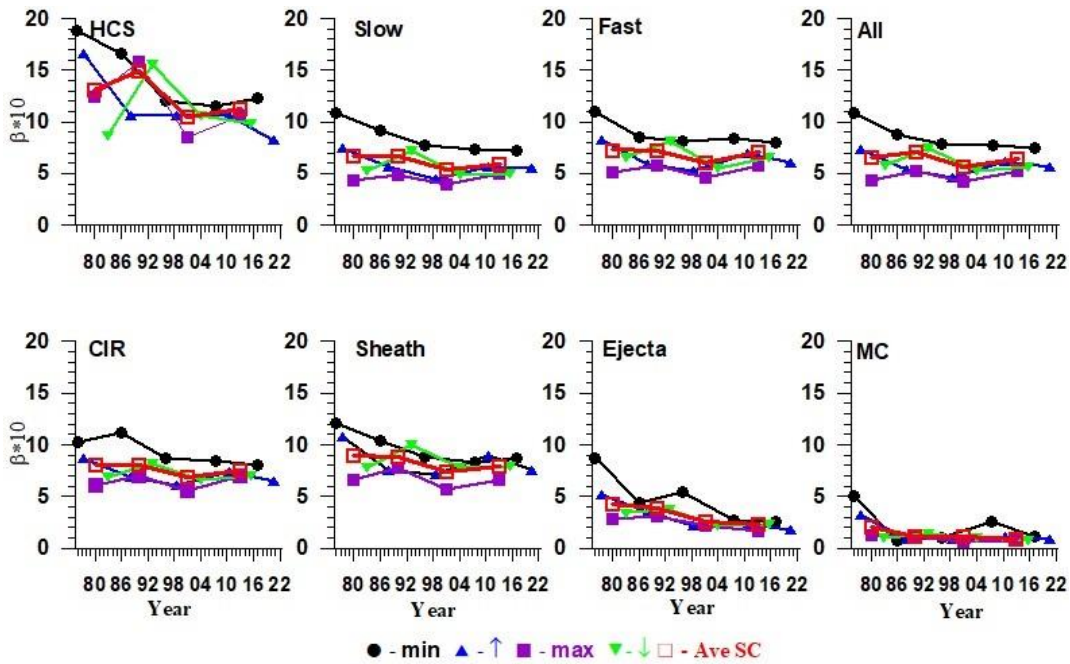

Figure 6. Time profiles of the proton β parameter

23 there is a decrease in the magnetic field. For quasi-stationary SW (HCS, Slow, and Fast) and without SW type selection (All), *B* remains unchanged or increases slightly compared to the previous minimum phase and the rising phase of SC 24.

It is interesting to compare the time profiles of the dimensionless β value, the ratio of the proton thermal pressure to the magnetic pressure (Figure 6). For all SW types, unlike the parameters shown in the previous figures, the β parameter is high at solar minimum and low at solar maximum throughout the period and demonstrates a slight decrease during the epoch of solar activity decrease in SCs 23 and 24. During the rising phase of SC 25, the β parameter behaves similarly to SC 24. Unlike SC 24, during the rising phase of SC 25 there is a slight tendency for the β parameter in the disturbed SW types (CIR, Sheath, Ejecta, and MC) to decrease. This can be assumed to be due to the appearance of a larger number of sufficiently disturbed SW types during this period than during the same period of SC 24.

The relative density of alpha particles N_α/N_p is shown in Figure 7, which indicates that for all SW types N_α/N_p is maximum at solar maximum and minimum at

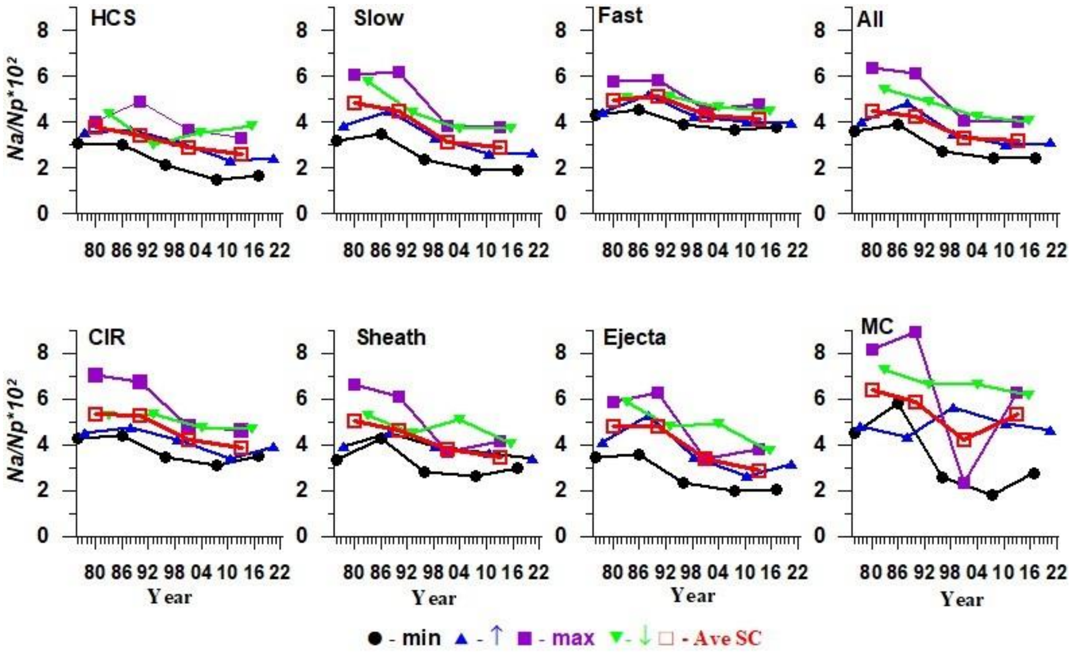

Figure 7. Time profiles of relative helium abundance N_α/N_p

Table 2

Behavior of parameters during transition from the minimum phase to the rising phase for solar cycles 23/24 and 24/25 (Figures 2–7)

	HCS	Slow	Fast	All	CIR	Sheath	Ejecta	MC
V	+	+	+	+	+	–	+	+
T	+	+	+	+	+	–	+	–
N	–	–	+	+	+	–	+	–
B	+	+	+	+	–	+	+	–
β	+	+	+	+	+	–	+	+
N_α/N_p	+	+	+	+	+	+	+	+

solar minimum, and during the epoch of low solar activity in SCs 23–24 it decreased ~1.5 times. It is significant that if the proton density N_p decreased by ~40 %, the absolute alpha particle density N_α dropped ~2 times. For all SW types during the rising phase, N_α/N_p increases as compared to the phase of the previous minimum, and during the rising phase of SC 25 N_α/N_p behaves similarly to that during the rising phase of SC 24.

3. DISCUSSION AND CONCLUSIONS

In this paper, we have calculated average parameter values for the data sets obtained by selecting the OMNI database data [King, Papitashvili, 2005] for 1976–2022, both by phases of the 11-year solar cycle and by large-scale solar wind types, from the catalog [http://www.iki.rssi.ru/pub/omni; Yermolaev et al., 2009]. In contrast to the previous work [Yermolaev et al., 2021a], here for the first time we have thus calculated the average parameter values during the rising phase of SC 25 and have compared them with the values during similar phases of previous low solar activity cycles 23 and 24.

Table 2 summarizes the behavior of the parameters V, T, N, B, β, and N_α/N_p during the transition of solar activity from the minimum phase to the rising phase for the previous and current solar cycles: similar behavior is marked with "+"; and the difference, with "–". All the parameters behave similarly for the data without selecting the solar wind type (All), Fast and Ejecta. The difference in one parameter is observed for HCS (for N), Slow (for N), and CIR (for B). The difference in the largest number of parameters is seen for Sheath and MC. As we have already mentioned, the statistical significance is the least for MC due to the small number of events. This analysis suggests that there is no significant reason to believe that the beginning of current SC 25 differs from the beginning of the previous cycle, and the continuation of this cycle will most likely be similar to the corresponding phases of previous SC 24, i.e. SC 25 will be weaker than SCs 21 and 22.

Our determination of the time limits of the rising phase of SC 25 is rather arbitrary since it is difficult to do for a cycle that has not yet ended. For the data to have sufficient statistical reliability, we use the annually averaged data from our catalog during pre-selection. The selected intervals of solar cycle phases are, therefore, a compromise between the phase boundaries determined from solar data and from solar wind observations from our catalog. The purpose of this work is to qualitatively assess the behavior of SC 25 by comparing the results of similar analysis of solar wind data for previous cycles, and, in our opinion, the results obtained allow us (with all the reservations made) to qualitatively answer the question about the further development of SC 25. Given the above conclusion about weak SC 25, we cannot exclude that the period 2021–2022 includes measurements related to the maximum phase of SC 25. Nonetheless, their inclusion in our analysis would only strengthen these trends, whereas the resulting dependences were so weak that they did not allow us to conclude that the rising phase of SC 25 differs from the same phase of SC 24. The boundaries of the rising phase of SC 25 adopted in this work, possibly partially covering the maximum phase, cannot therefore significantly affect the conclusions.

The prediction of the development of solar activity in the coming years and, in particular, in SC 25 remains debatable and is widely discussed in the literature [Du, 2023; Peguero, Carrasco, 2023; Coban et al., 2021; Nagovitsyn, Ivanov, 2023; Prasad et al., 2023; Zharkova et al., 2023; Javaraiah, 2023]. We hope that the results reported in this paper will provide a deeper insight into the development of solar activity in the current solar cycle and beyond.

We are grateful to creators of the databases [https://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni] and [http://www.iki.rssi.ru/pub/omni] for the opportunity to use them in this work.

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