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Some Features of the Present-day Transition Period in Solar Activity

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Abstract—Various geophysical indices and their prognostic value were analyzed in (Obridko et al., 2013; Kirov et al., 2013, 2015, 2017; Georgieva et al., 2015, 2018). Two indices have been selected for the analysis (total annual *Dst* values, and duration of a storm). It is important to note that, unlike the other indices of solar and geophysical activity, the summary *Dst* index does not show violation of the Gnevyshev-Ohl rule. The analysis of annual mean *Dst* values reveals a clearly pronounced decrease in activity, at least since the 1980-ies. This allows us to suggest that we are at the descending branch of a secular cycle or on the threshold of a Grand Minimum. The decrease in solar activity is corroborated by the analysis of Forbush effects, solar wind speed, and intensity of the near-Earth magnetic field.

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1. INTRODUCTION

At the end of the XX century, a number of authors put forward the idea of gradual increase in solar and geomagnetic activity. In the fundamental work by Lockwood et al. (1999), it was shown that the radial component of the interplanetary magnetic field increased 1.4 times from 1964 to 1995. The authors restored the interplanetary magnetic flux from aa-index data and arrived at the conclusion that the interplanetary magnetic field had increased by a factor of 2.3 since 1901. The same conclusion was drawn by Makarov et al. (2001, 2002), who analyzed the positions of the large-scale magnetic-field boundaries restored from observations of Hα filaments. It should be noted, however, that both Lockwood et al. and Makarov et al. based their conclusions on the increasing activity during the first 80 years of the XX century. The apparent decline after 1980 in Fig. 5 in (Makarov et al., 2001, 2002) was interpreted as transition to the next minimum of the 11-year cycle, rather than the onset of a long-term decline.

The very high Cycle 19 was followed by a decline. The height of Cycle 20 was almost strictly medium and, in accordance with the Gnevyshev-Ohl rule, the next Cycle 21 was higher than medium. Then, however, surprises began. Cycle 22 was not low. On the contrary, it exceeded in height even quite a high Cycle 18. And further, the height of the cycles began to decrease violating the Gnevyshev-Ohl rule.

By that time, evidence had emerged indicating that we were approaching the period of a few abnormally low cycles. In (Duhau, 2003), it was shown that the ratio of heights of the even and odd cycles changed with time and could be violated not only in the pair of Cycles 22–24, but also in the pair of Cycles 24–25. The height of Cycle 24 was predicted to equal 87.5 ± 23.5[1]. The work by Obridko and Shelting (2009), which is actually a continuation of the study by Makarov et al. (2001, 2002), is dealing with anomalies in the solar magnetic field and the meridional-circulation asymmetry. It shows that the strength of the polar magnetic field was decreasing systematically during the past three cycles. This is due to the fact that the increase in the dipole magnetic moment observed from 1915 to 1976 gave way to a decrease during the following three cycles.

These data were interpreted as indication to a possible advent of a Maunder-type minimum or at least a sequence of a few low cycles.

Ogurtsov (2005), based on an analysis of the paleo-catastrophic reconstruction of solar activity spanning more than 10000 years, concluded that the average level of solar activity in the 21st century is likely to decrease, but the likelihood of a deep minimum is low.

The process of transition was analyzed in detail by De Jager et al. (2016), who arrived at a conclusion that the first signatures of transition to a Grand Minimum had been noticed as early as in the 1960-ies. According to (Obridko and Shelting, 2009), the transition period started approximately in 1982. In any case, the transition is not abrupt, but takes quite a long time.

[1] Hereinafter, in quoting early works, we give the original sunspot numbers in the system generally accepted at that time. This system corresponds to Version 1 (http://sidc.oma.be/silso/).

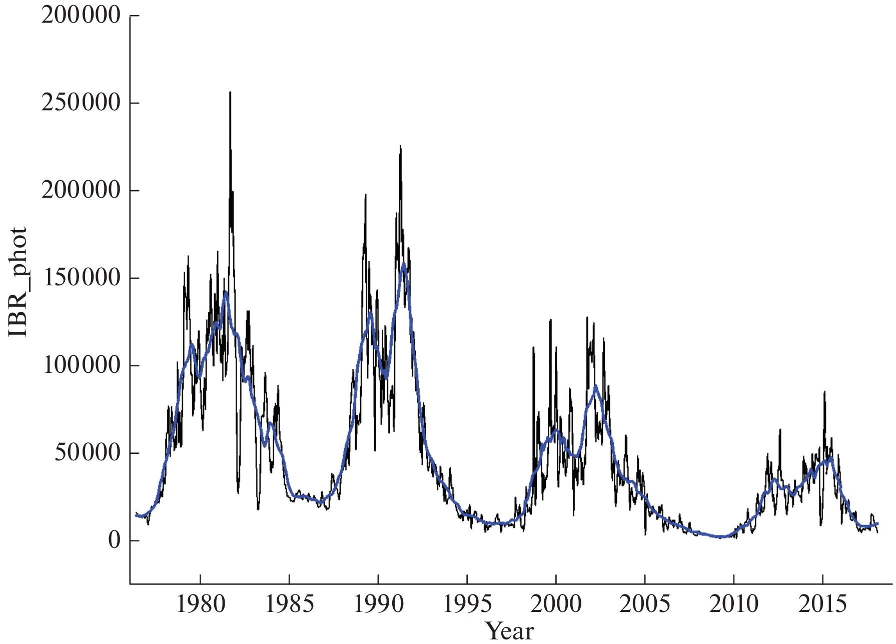

Fig. 1. Squared radial magnetic field I_{BR}-*phot*. averaged over the entire solar surface (black line – data for each Carrington rotation, blue line – smoothing over 13 points).

It should be noted that there were plenty of daring publications, which predicted with large anteriority a strong decrease in solar activity in the first half of the XXI century. The first one we are aware of was the work by Chistyakov (1983). Based on the analysis of the secular cycle, he predicted the heights of maxima of Cycles 22, 23, and 24 equal, respectively, to 102, 75, and 88. Anyway, his prediction for Cycle 24 is very close to the observed value. For Cycle 25, Chistyakov gives the value 121, which is somewhat higher than the mean for all previous cycles. Simultaneously, another research team (Kontor et al., 1983) focused on the analysis of the envelope of the cycle maxima and predicted the variation of solar activity up to Cycle 44(!), whose maximum they dated as 2235 forecasting for that time a new Maunder-type minimum. For Cycles 22–23 their forecast was 106, 110, and 113, respectively. For Cycle 25, they predicted the maximum sunspot number 117, which virtually coincides with the mean value for the past 23 cycles. A similar situation was observed at the beginning of the XIX and XX centuries. R. Kane (2002), guided by the concept of a secular cycle, believed that we would witness a sequence of cycles decreasing gradually in height during the following 50 years.

Bonev (1997) and Tlatov (2014) arrived at the same conclusion. Besides, they admit the change of sign in the Gnevyshev-Ohl rule beginning with Cycle 22.

The present-day prognostic characteristics are discussed in more detail in (Obridko and Nagovitsyn, 2017).

Thus, we can expect one or two cycles of moderate or low activity at the beginning of the XXI century. This resembles the Dalton minimum at the beginning of the XIX century. However, a more profound decline of the type of Maunder minimum cannot be ruled out, although it is less probable (see the special issue of JASTP and the introductory article by Obridko and Georgieva (2018)).

A gradual decrease of the solar magnetic field is illustrated in Fig. 1, which shows the time dependence of the square of the radial magnetic field averaged over the entire solar surface (index I_{BR}-*phot*).

A decrease in solar activity can be also traced by changes in the solar-related geophysical parameters. This was noted in many papers, including some of those cited above.

Various geophysical indices and their prognostic value were analyzed in (Obridko et al., 2013; Kirov et al., 2013, 2015, 2017; Georgieva et al., 2015, 2018). It is very important to bear in mind that both the solar activity and its geophysical effects comprise a complex of different processes connected in different ways. In particular, the sudden- and gradual-commencement geomagnetic disturbances are definitely associated with different events in the Sun and should be taken into account separately when issuing a forecast. We start this paper with the analysis of geomagnetic disturbances and later turn to the analysis of other indices.

2. CYCLE VARIATIONS IN THE GEOMAGNETIC ACTIVITY INDICES

Before we turn to the analysis of long-term relations, let us consider again the cycle variation of geo-

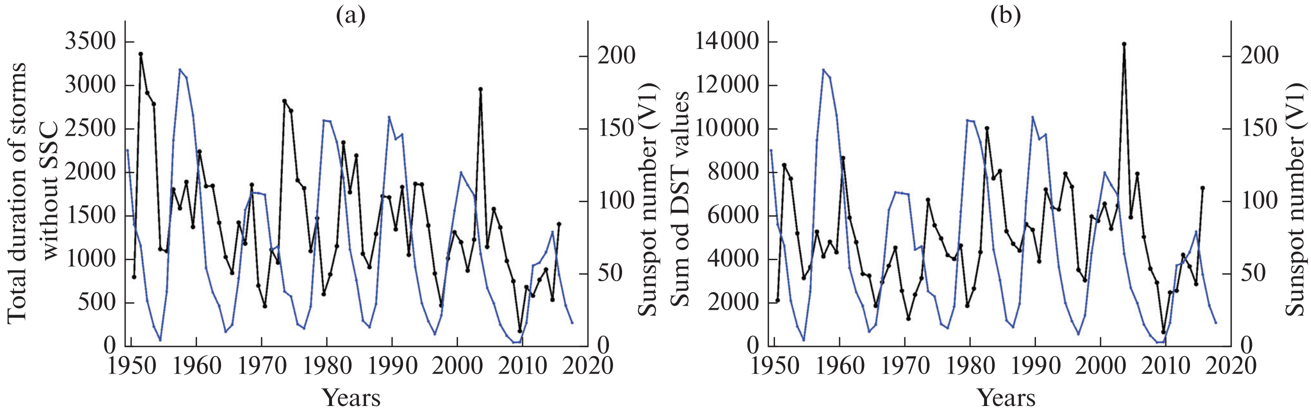

Fig. 2. Variations in total annual cumulative duration in hours, and total cumulative sum of absolute *Dst* values for storms without sudden commencement. The blue curve represents the sunspot number (Version 1).

magnetic disturbances. It was shown that the storm sudden commencement (SSC) is associated with coronal mass ejections, which, in turn, are closely related to active regions in the Sun. This suggests a high correlation between the number of SSC and sunspot number. The situation is different in the case of gradual-commencement storms. The source of these storms is the fast solar wind flowing out of coronal holes (CH). Coronal holes usually reach their maximum both in area and in occurrence rate in the decline phase of the activity cycle. Therefore, the gradual-commencement storms correlate weakly with sunspot numbers. The relationship with the activity cycle can only be revealed when considering the time shift of CH number relative to the sunspot cycle, which moreover is not constant.

This study is based on the data from the catalog http://www.izmiran.ru/magnetism/magobs/MagneticStormCatalog.html used in our earlier work (Obridko et al., 2013; Kirov et al., 2013) and supplemented with new data for Cycle 24. The papers cited above were mainly focused on the annual number of storms. In this work, we are using two new non-standard integral parameters of geomagnetic storms: the total annual duration and the *Dst* total annual absolute value. These cumulative parameters are convenient because they characterize the total disturbance level in a given year.

2.1. Gradual Storm Commencement

Figure 2 shows variations in total year cumulative duration in hours, and total cumulative sum of absolute *Dst* value for storms with gradual commencement. The blue curve represents the sunspot number (Version 1).

It is interesting to note that the Gnevyshev-Ohl rule (i.e., the even cycle is always lower than the following odd cycle) manifests itself differently in the three indices we have introduced. As is known, this rule was fulfilled nearly all over the epoch of reliable observations of sunspots. During the period under examination, it was true in Cycles 18–19 and 20–21, but was violated in Cycles 22–23 (shown in bold below).

M18 < M19, M20 < M21,
M22 > **M23** sunspot number,

M18 > **M19**, M20 < M21,
M22 > **M23** number of storms,

M18 > **M19**, **M20** > **M21**,
M22 < M23 total duration,

M18 < M19, M20 < M21,
M22 < M23 summary *Dst*.

Each of the indices introduced has its own peculiarities. In the number of storms, the Gnevyshev-Ohl rule was violated not only in Cycles 22–23, but also in cycles 18–19. In the total duration of storms, it was violated in Cycles 18–19 and 20–21, but was fulfilled in Cycles 22–23, where it was violated in the sunspot number index. And finally, in the summary *Dst* index the Gnevyshev-Ohl rule was fulfilled in all pairs of cycles. Since the gradual-commencement storms depend on the number and area of coronal holes in the Sun, it can be assumed that the index we have introduced reflects the intensity of global process of solar activity.

2.2. Sudden Storm Commencement

Storms with sudden commencement are determined by non-stationary processes in the Sun, primarily, by coronal mass ejections. Since the latter are mainly the result of local activity, it can be expected that the cyclic behavior of the three indices under consideration would be similar to the sunspot number cyclic variation. A comparison is represented in Fig. 3.

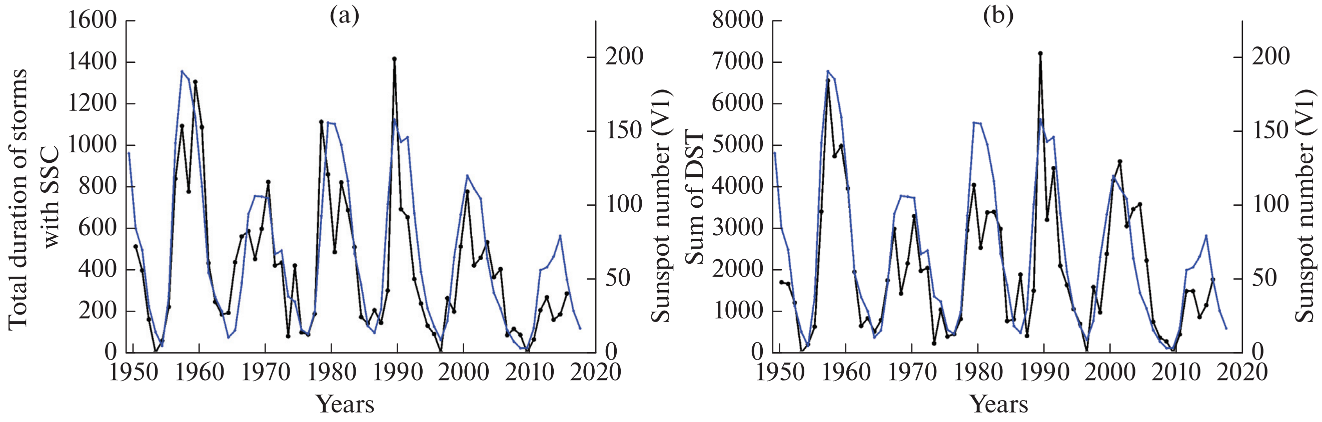

Fig. 3. Variations in total annual cumulative duration in hours, and total cumulative sum of absolute *Dst* values for storms with with sudden commencement. The blue curve represents sunspot numbers.

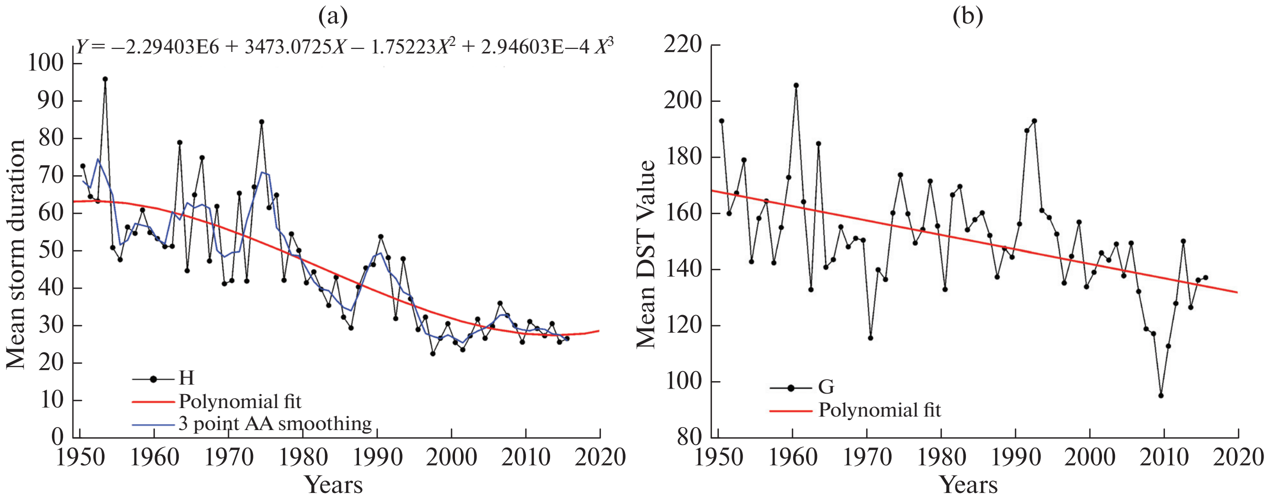

Fig. 4. Gradual decrease in mean storm duration in hours and mean *Dst* values with time for storms without Sudden storm commencement.

As expected, the temporal characteristics of all three indices are consistent with those of sunspot numbers. The Gnevyshev-Ohl rule is or is not fulfilled in the same pairs of cycles as in sunspots. In Cycles 21 and 24, the *Dst* values are relatively low.

3. TIME DEPENDENCE OF THE MEAN DURATION AND MEAN INTENSITY OF MAGNETIC STORMS

The indices of total duration described above allow us to find the mean storm duration (*H*) and the *Dst* mean value (*G*). These indices indicate a gradual decrease in geophysical activity with time (see Figs. 4 and 5).

All indices decrease noticeably with time. The decrease manifests itself most clearly in the mean storm duration index. The mean duration of gradual-commencement storms has decreased 2.6 times (from 65 hours to 25 hours) and the mean duration of sudden-commencement storms has decreased from 55 to 25 hours (i.e., 2.2 times). The *Dst* mean value for both types of storms has decreased by 20–25%.

4. LONG-TERM CHANGES IN THE FORBUSH EFFECT

Besides the geomagnetic storms, the interplanetary disturbances manifest themselves in cosmic rays in the form of Forbush decreases. In other words, cosmic rays carry information on the state of the interplanetary medium. If they encounter a magnetic irregularity on their way, it will necessarily be reflected in cosmic ray variations. In turn, the state of the interplanetary medium is controlled directly by the solar activity.

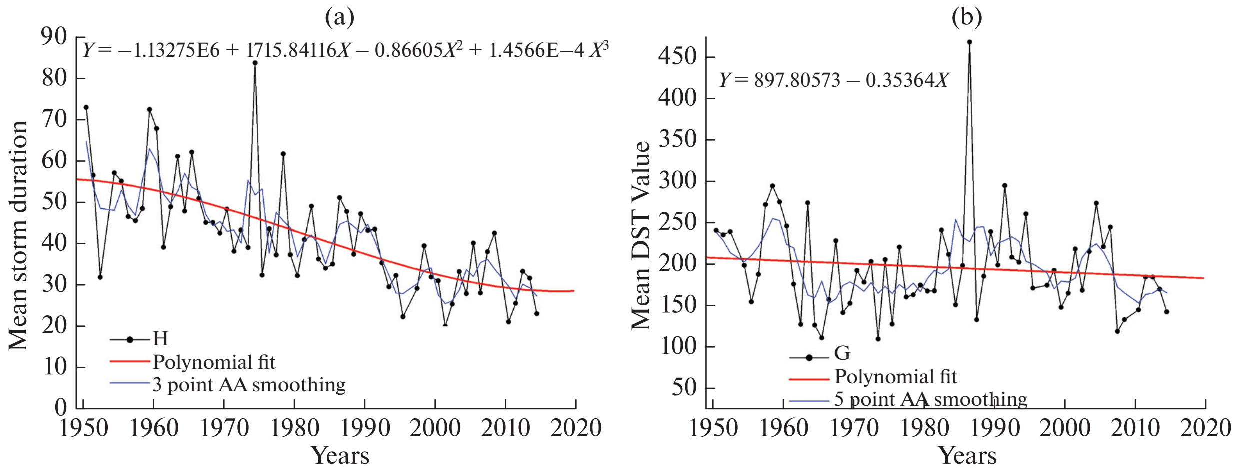

Fig. 5. Gradual decrease in mean storm duration in hours and mean *Dst* values with time for storms with Sudden storm commencement.

Both the intensity of geomagnetic storms and the parameters of the Forbush effect depend on interplanetary parameters. The difference is that the former depends on local conditions at the Earth position in the medium (solar wind velocity, magnitude and orientation of *Bz* field component, etc.), while the latter are determined by global parameters, such as the intensity of the interplanetary magnetic field, the global size of the disturbance, etc. It is important to emphasize that hereinafter we are not talking of data from a single neutron monitor, but consider cosmic ray variations obtained with the global survey method, where the data are provided by the worldwide network of neutron monitors used as a single multi-directional device (see, for example, (Belov et al., 2018a, b)).

It is to be noted that the parameters of Forbush decrease differ in the events with sudden onset (which coincide with sudden geomagnetic storm commencements or interplanetary shocks – *SSC group*) and those with gradual onset (*noSSC group*). Abunin et al. (2012) revealed these differences using a statistical comparative analysis. The results obtained indicate that the mechanisms of modulation of galactic cosmic rays in the selected groups are different. The SSC-group events are largely due to the emission of solar matter from active regions, while a significant part of the events of noSSC group are high-speed plasma flows from coronal holes and filament ejections.

As for long-term variations in galactic cosmic rays, Melkumyan et al. (2018) analyzed a large number of events to study the long-term changes in the number and value of Forbush effects. They showed that solar activity cycles are well manifested in the Forbush-effect data, especially in major events, which almost disappear in the epochs of minimum. The changes in the distribution of Forbush effects and the decrease in their mean value from maximum to minimum of the activity cycle were explained by the fact that cosmic ray variations in the periods of low activity are mainly due to coronal holes. The authors of the cited work have noted that Forbush effects in the current cycle are fewer in number and, on the whole, weaker than in the previous five cycles. They introduced and calculated an FD-index, which combines the intensity and number of Forbush effects and is convenient for studying long-term variations. In the same work, they proposed supplementing the study with an analysis of the annual total and annual mean parameters of Forbush effects.

Figure 6a, b show long-term variations in the annual mean Forbush effect amplitudes (FE) during the noSSC and SSC events, respectively. The noSSC events display a gradual decrease in the annual mean amplitudes, which is absent in the SSC events. This may be due to several reasons. First, one can see that Cycle 19 responsible for the overall decrease stands out in Fig. 6a. Indeed, Cycle 19 was unique in the history of solar-activity observations over the past 250 years. The largest number of sunspots and the largest ground-level enhancement of solar cosmic rays (GLE05, February 1956) were recorded in that period (e.g., see (Belov et al., 2006; Miroshnichenko, 2001; Shea and Smart, 2002; Smart and Shea, 1990)). The monthly mean geomagnetic activity in September 1957 was the highest over the past six cycles. Two out of the three most active months belong to Cycle 19, which also accounts for 1/3 of all extreme geomagnetic storms that occurred during the past six cycles (Abunin et al., 2013).

Second, in Cycle 19, it is difficult to isolate individual events, because solar wind measurements, gamma-ray observations, data on coronal mass ejections, etc. were virtually absent at that time. The events in cosmic rays were mainly identified from geomagnetic activity and cosmic ray variations (Abunin et al., 2013). Thus, it is very likely that minor Forbush effects, which were plenty in Cycle 19, merged with the larger ones.

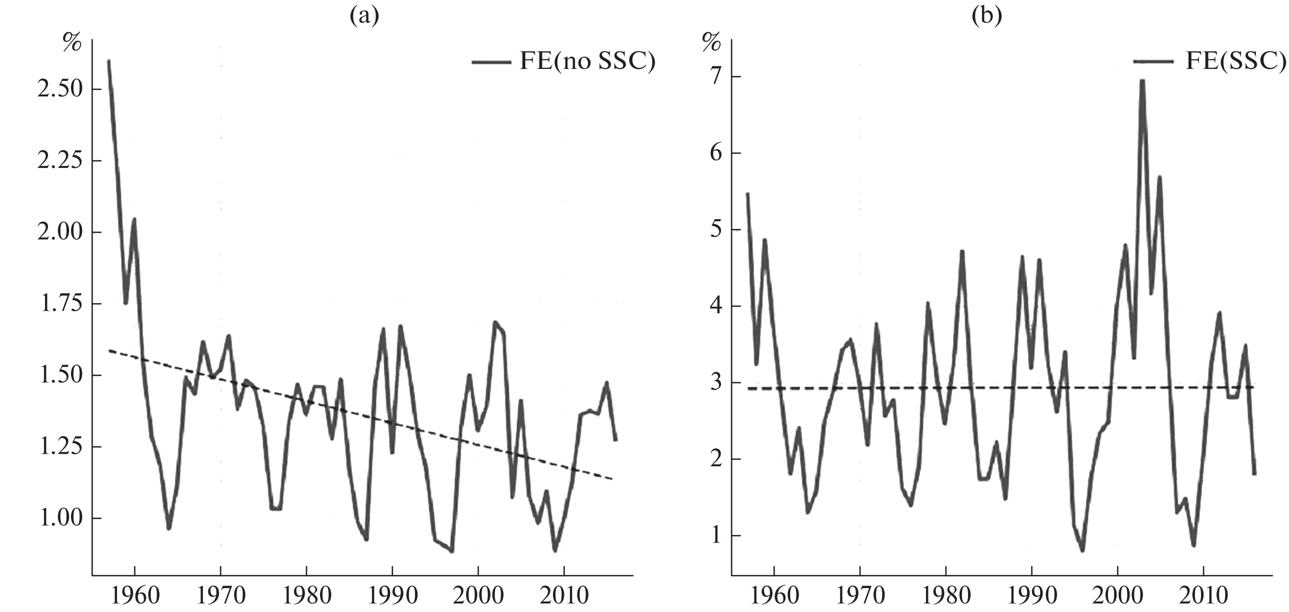

Fig. 6. Annual mean amplitudes of Forbush decrease in noSSC (a) and SSC (b) events.

As for SSC events, Fig. 6b does not display any apparent decrease or increase in the annual mean Forbush-effect amplitudes. Here, one can see some notable features, e.g., in Cycle 23, but this is the subject of a different scientific study.

A distinct trend appears if we consider the total annual variations in the Forbush effect parameters instead of their annual mean (or median) values. In this case, for example, errors in the selection of individual events are excluded (see Fig. 7a–d).

Figure 7a, b represent long-term variations in the total annual amplitudes of Forbush effects in the noSSC and SSC events, respectively. Both figures display a pronounced downward trend. A reason for such a trend may be a change in the interplanetary disturbances themselves, i.e., a decrease in the disturbance magnetic field, size, etc., which determine the Forbush effect parameters. The smaller the field and size of a disturbance, the smaller the value and other parameters of the Forbush effect.

The situation with long-term variations in the total annual duration of the main (decay) phase $T_{\min}$ of Forbush effects in the noSSC and SSC events is even more interesting (see Fig. 7c, d, respectively). $T_{\min}$ is the time between the onset of the Forbush effect and the minimum density of cosmic rays.

In the case of SSC events (Fig. 7d), we see a decrease, which also confirms the change in the parameters of disturbances accompanied by a shock wave. Since the main sources of interplanetary disturbances accompanied by a shock wave or a sudden storm commencement are coronal mass ejections, it can be assumed that they become weaker (in field, propagation velocity, etc.) and powerful CMEs more rare.

On the contrary, the duration of the main phase of the Forbush effect in the noSSC events (Fig. 7c) increases. This may be due to the fact that the speeds of disturbances (high-speed streams from coronal holes, filament events, weak ejections from active regions, etc.) decrease with time and, as a result, the main phase of the Forbush effect lasts longer.

5. MAGNETIC FIELD AND VELOCITIES IN THE HELIOSPHERE

Thus, based solely on the data on long-term variations in the characteristics of the Forbush effect, we can suggest that interplanetary disturbances determined directly by the solar activity have been changing (weakening) starting with Cycle 19.

Consider now the data of direct observations in the interplanetary medium. We have calculated the magnetic field and dynamic pressure for three geoeffective factors (slow solar wind along the heliospheric current sheet; high-speed solar wind from large polar coronal holes at solar minimum and from smaller low-latitude coronal holes at maximum; and CMEs).

Figure 8 illustrates the time dependence of these parameters. The thin solid line shows the annual mean values, the thick line is the result of filtration (smoothing over a 13-year window), and the dotted line shows (for reference) the International sunspot numbers (version 1).

Starting with 1982, all these sources display a significant decrease. For the sources associated with the solar wind, the magnetic field has decreased by 20%,

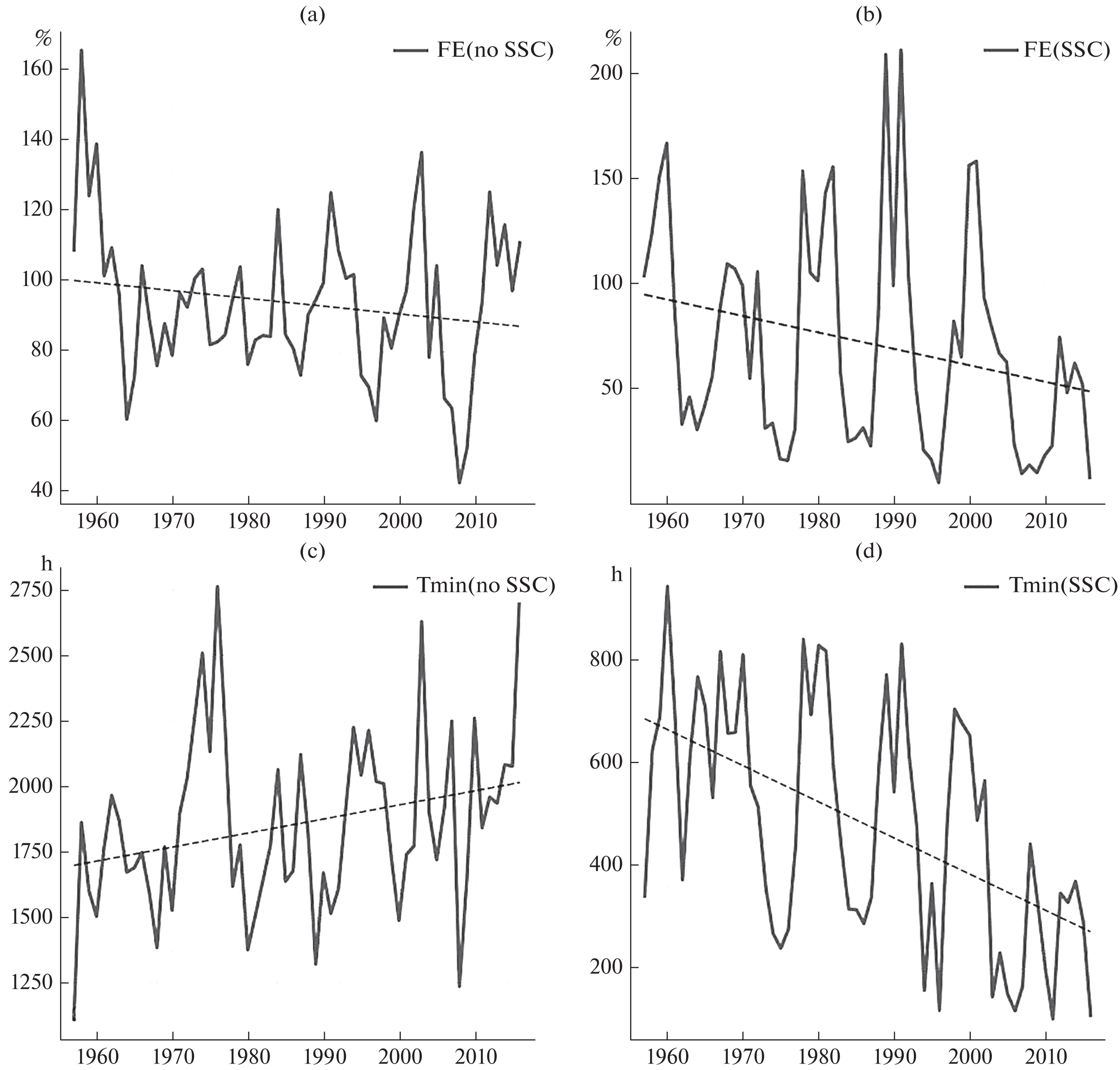

Fig. 7. Long-term variations in the total annual values of the Forbush-effect parameters: (a) and (b) – Forbush effect amplitudes in the noSSC and SSC events, respectively; (c) and (d) – duration of the Forbush effect main phase (decay phase) in the noSSC and SSC events, respectively.

and the dynamic pressure, by about 45%. For CMEs, the decrease is not as large: ~12.5% in magnetic field and 26% in dynamic pressure.

6. DISCUSSION OF RESULTS

In this paper, we have confirmed that geomagnetic storms with a sudden and gradual commencement have different solar sources. In particular, it is important to note that, unlike the other indices of solar and geophysical activity, the summary *Dst* index does not manifest violation of the Gnevyshev-Ohl rule.

The characteristics of SSC events reveal their close relation to the indices of local activity in the Sun, in particular, the sunspot numbers.

The analysis of the annual mean values has revealed a clearly pronounced trend towards a decrease of activity, at least since the 1980-ies. This allows us to suggest that we are at the descending branch of a secular cycle or on the threshold of a Grand Minimum. It should be noted that the decrease

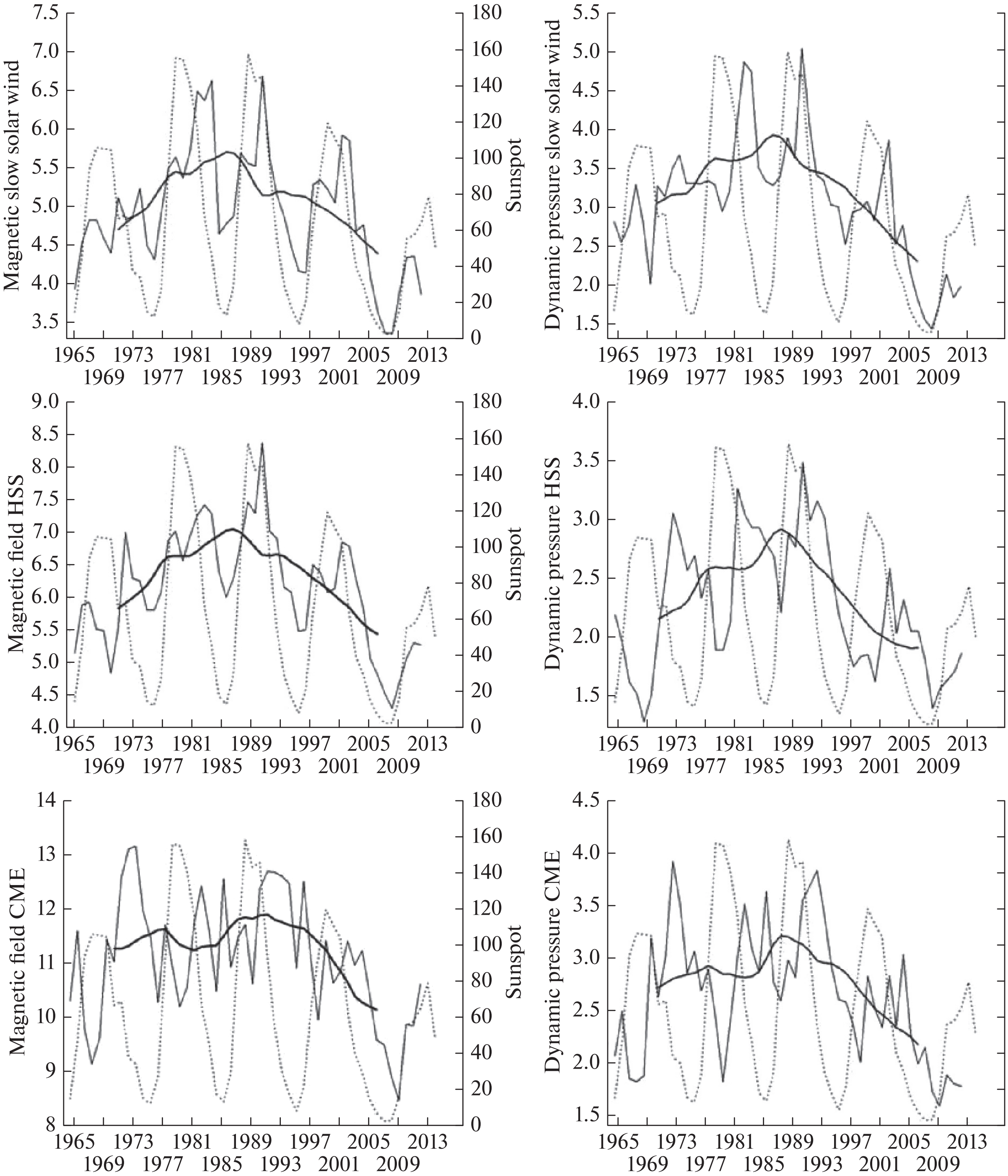

Fig. 8. Time variations in the magnetic field and dynamic pressure for three types of the solar wind. The thin solid line shows the annual mean values, the thick line smoothed over a 13-year window, and the dotted line shows (for reference) the International sunspot numbers (version 1).

in SSC events is somewhat smaller than in the noSSC events.

The presence of a secular trend in the annual mean characteristics of the events associated with CMEs is of particular importance. The fact is that the actual annual number of CMEs in Cycle 24 slightly differs from that recorded in Cycle 23.

It seems that, while the annual numbers of the events remain virtually unchanged (Fig. 9), the number of intensive events decreases. It is the above-noted tendency towards a decrease in the characteristic space scales of the activity objects and a relatively increasing population of minor features (such as small sunspots, small coronal holes with decreased magnetic field,

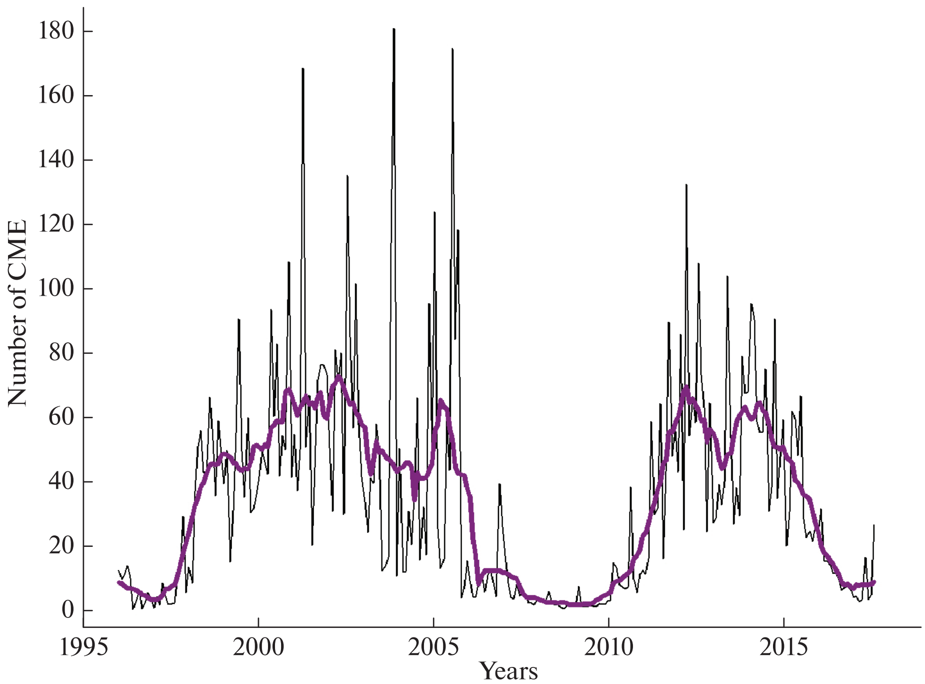

Fig. 9. Monthly (thin curve) and annual (thick curve) numbers of coronal mass ejections.

etc.) that may result in the advent of low activity cycles and even grand-minima of the type of the Maunder minimum.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

Abunin, A.A., Abunina, M.A., Belov, A.V., et al., Forbush effects with sudden and gradual onset, *Geomagn. Aeron. (Engl. Transl.)*, 2012, vol. 52, no. 3, pp. 291–300. https://doi.org/10.1134/S0016793212030024

Abunin, A.A., Abunina, M.A., Belov, A.V., et al., Forbush-decreases in 19th solar cycle, *J. Phys.: Conf. Ser.*, 2013, vol. 409, 012165. https://doi.org/10.1088/1742-6596/409/1/012165

Belov, A.V., Eroshenko, E.A., Yanke, V.G., and Mavromichalaki, E., Proton event of February 23, 1956 according to neutron monitor data, *Izv. Ross. Akad. Nauk.: Ser. Fiz.*, 2006, vol. 69, no. 6, pp. 901–904.

Belov, A., Eroshenko, E., Yanke, V., et al., The global survey method applied to ground-level cosmic ray measurements, *Sol. Phys.*, 2018a, vol. 293, id 68. https://doi.org/10.1007/s11207-018-1277-6

Belov, A.V., Eroshenko, E.A., Yanke, V.G., et al., Global survey method for the world neutron monitor network, *Geomagn. Aeron. (Engl. Transl.)*, 2018b, vol. 58, no. 7, pp. 356–372. https://doi.org/10.1134/S0016793218030039

Bonev, B., Estimating the course of the solar activity in the end of 20th and beginning of 21st century on time variations within the Zurich series, *Bulg. Geophys. J.*, 1997, vol. 13, p. 43.

Chistyakov, V.F., A forecast of solar activity till the year 2030, *Soln. Dannie*, 1983, no. 1, pp. 97–100.

De Jager, C., Akasofu, S.-I., Duhau, S., et al., A remarkable recent transition in the solar dynamo, *Space Sci. Rev.*, 2016, vol. 201, pp. 109–145. https://doi.org/10.1007/s11214-016-0293-9

Duhau, S., An Early Prediction of Maximum Sunspot Number in Solar Cycle 24. *Sol. Phys.*, 2003, vol. 213, pp. 203–212. https://doi.org/10.1023/A:1023260916825

Georgieva, K., Kirov, B., Nagovitsyn, Yu., and Obridko, V., Sunspot cycle 24: is Sun entering a grand minimum? In *Solnechnaya i solnechno-zemnaya fizika* (Solar and Solar–Terrestrial Physics), Pulkovo, 2015, p. 71.

Georgieva, K., Kirov, B., and Obridko, V.N., Long-term variations in the solar wind components and their terrestrial effects, in *Solnechnaya i solnechno-zemnaya fizika* (Solar and Solar–Terrestrial Physics), Pulkovo, 2018, p. 103.

Kane, R.P., Prediction of solar activity: Role of long-term variations, *J. Geophys. Res.: Space Phys.*, 2002, vol. 107, no. A7, SSH 3-1. https://doi.org/10.1029/2001JA000247

Kirov, B., Obridko, V.N., Georgieva, K., et al., Long-term variations of geomagnetic activity and their solar sourc-

es, *Geomagn. Aeron. (Engl. Transl.)*, 2013, vol. 53, no. 7, pp. 813–817.
https://doi.org/10.1134/S0016793213070128

Kirov, B., Asenovski, S., Georgieva, K., and Obridko, V.N., What causes geomagnetic activity during sunspot minimum? *Geomagn. Aeron. (Engl. Transl.)*, 2015, vol. 55, no. 8, pp. 1033–1038.
https://doi.org/10.1134/S0016793215080149

Kirov, B., Asenovski, S., Georgieva, K., et al., Forecasting the sunspot maximum through an analysis of geomagnetic activity, *J. Atmos. Sol.-Terr. Phys.*, 2017, vol. 176, pp. 42–50.
https://doi.org/10.1016/j.jastp.2017.12.016

Kontor, N.N., Lyubimov, G.P., Pereslegina, and N.V., Khotilovskaya, T.G., Forecast of maximum sunspot numbers in cycles 22–24, *Soln. Dannie*, 1983, no. 11, p. 74.

Lockwood, M., Stamper, R., and Wild, M.N., A doubling of the Sun's coronal magnetic field during the past 100 years, *Nature*, 1999, vol. 399, pp. 437–439.
https://doi.org/10.1038/20867

Makarov, V.I., Obridko, V.N., and Tlatov, A.G., The increase in the magnetic flux from the polar regions of the Sun over the last 120 years, *Astron. Rep.*, 2001, vol. 45, pp. 746–750.
https://doi.org/10.1134/1.1398924

Makarov, V.I., Tlatov, A.G., Callebaut, D.K., and Obridko, V.N., Increase of the magnetic flux from polar zones of the Sun in the last 120 years, *Sol. Phys.*, 2002, vol. 206, pp. 383–399.
https://doi.org/10.1023/A:1015062615953

Melkumyan, A.A., Belov, A.V., Abunina, M.A., et al., Long-term changes in the number and magnitude of Forbush effects, *Geomagn. Aeron. (Engl. Transl.)*, 2018, vol. 58, no. 5, pp. 615–624.
https://doi.org/10.1134/S0016793218050109

Miroshnichenko, L.I., *Solar Cosmic Rays*, Kluwer Academic, 2001.

Obridko, V. and Georgieva, K., Solar activity in the following decades, *J. Atmos. Sol.-Terr. Phys.*, 2018, vol. 176, pp. 1–4.
https://doi.org/10.1016/j.jastp.2018.08.001

Obridko, V.N. and Nagovitsyn, Yu.A., *Solnechnaya aktivnost', periodichnost' i metody prognoza* (Solar Activity, Periodicity, and Prediction Methods), St. Petersburg: Izdatel'stvo VVM, 2017.

Obridko, V.N. and Shelting, B.D., Anomalies in the evolution of global and large-scale magnetic fields in the Sun as precursors of several future low cycles, *Astron. Lett.*, 2009, vol. 35, pp. 247–252.
https://doi.org/10.1134/S1063773709040045

Obridko, V.N., Kanonidi, Kh.D., Mitrofanova, T.A., and Shelting, B.D., Solar activity and geomagnetic disturbances, *Geomagn. Aeron. (Engl. Transl.)*, 2013, vol. 53, no. 2, pp. 147–156.
https://doi.org/10.1134/S0016793213010143

Ogurtsov, M. G., On the possibility of forecasting the Sun's activity using radiocarbon solar proxy, *Sol. Phys.*, 2005, vol. 231, pp. 167–176.
https://doi.org/10.1007/s11207-005-8775-z

Shea, M.A. and Smart, D.F., Solar proton event patterns: the rising portion of five solar cycles, *Adv. Space Res.*, 2002, vol. 29, no. 3, pp. 325–330.
https://doi.org/10.1016/S0273-1177(01)00592-0

Smart, D.F. and Shea, M.A., Probable pitch angle distribution and spectra of the 23 February 1956 solar cosmic ray event, in *Proc. 21st Int. Cosmic Ray Conf.*, Adelaide, 1990, vol. 5, pp. E257–E260.

Tlatov, A.G., The change of the solar cyclicity mode. *Adv. Space Res.*, 2014, vol. 55, no. 3, pp. 851–856.
https://doi.org/10.1016/j.asr.2014.06.024

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