

New Data about Long-Term Changes of Solar Activity¹

V. M. Efimenko^a, * and V. G. Lozitsky^a

^a*Astronomical Observatory of the Taras Shevchenko National University of Kyiv, Kyiv, 04053 Ukraine*

**e-mail: efim@observ.univ.kiev.ua*

Received February 27, 2018; in final form, March 7, 2018

Abstract—The double Hale cycle (about 44 years) was found in changes of power-law index for integral distributions of equivalent diameters of large groups of sunspots having sizes of 50–90 Mm. According to the Greenwich catalog data, this cycle is traced in the last 13 cycles of solar activity, nos. 12–24. In addition to this periodic change, a unique sporadic phenomenon was discovered, namely, a sharp jump in the maximum diameters of sunspot groups in the 18th cycle (more precisely, in 1946–1947), which has no analogues in other cycles.

DOI: 10.1134/S0016793218080066

1. INTRODUCTION

In the spectrum of solar activity fluctuations, many cycles have been discovered, among which the most powerful and studied is the 11-year cycle (Gnevyshev, 1977; Tsirolnik et al., 1997; Svalgaard et al., 2005). The Hale cycle with a period of about 22 years, corresponding to changes in the polarities of the magnetic fields of sunspots, also manifests itself quite clearly. There are also evidences of other cycles (Lean and Brueckner, 1989; Krivova and Solanki, 2002).

To further study the cyclicity of solar activity, it is important to use the longest and most homogeneous series of observations. As rule, series of Wolf numbers or of Zurich sunspot numbers are used for this purpose. However, these series have the drawback that they are formed by splitting all observed sunspots into groups of spots. At present, this partition is carried out on the basis of the magnetic polarities of sunspots (Hale and Nicholson, 1925). However, until 1925 this partitioning was carried out somewhat arbitrarily, according to the criteria for the appearance and compactness of the groups of spots, which, apparently, did not always coincide with the criterion of magnetic polarity. This introduced certain errors into the series of Wolf numbers. Therefore, for long time intervals covering the periods before and after 1925, it is more expedient to use such a parameter of solar activity, which does not depend on the polarities of sunspots. This parameter can be the area of the spots or their diameter, corrected for the effect of the projection. Namely such parameter was analyzed in papers by Babij et al. (2011), Munoz-Jaramillo et al. (2015), Efimenko and Lozitsky (2016), Nagovitsyn and Pevtsov (2016), Mandal and Banerjee (2016).

In paper by Babij et al. (2011), it was shown that the power-law index of integrated distribution of the sunspot diameters has certain variations, which are not the same in different 11-year cycles and at different phases of the same cycle. Since in this paper the data for the last 7 cycles only were analyzed, the conclusions obtained require a verification on a longer time interval. The purpose of this study is to revise the findings of this work on data related to the 13 last solar cycles.

2. OBSERVATIONAL DATA AND THEIR PRELIMINARY PROCESSING

The data on sunspot groups were used from the Greenwich directory and its extension NOAA-USEF (<http://solar.science.msfc.nasa.gov/greenwich/>). A detailed comparison of various directories made by Lozitska (2015) shows that Greenwich's data are most reliable, long-term and uniform.

In order to construct the integral dependences for the diameter of sunspots, equivalent diameters d_{eqv} of sunspot groups were determined. The d_{eqv} values were calculated by areas of sunspot groups, S_p , corrected for the effect of projection. To establish a link between d_{eqv} and S_p , single sunspots, round in shape, were specially selected, and on the basis of such sunspots the auxiliary gauge dependence was built (Efimenko and Lozitsky, 2016). For large sunspots, a simple approximate formula for linking the corrected areas and equivalent diameters was used: $d_{\text{eqv}} \approx 2(S_p)^{1/2}$, where d_{eqv} is expressed in mega-meters (Mm), and S_p in millionth parts of the hemisphere. Also, only large spots with diameters of more than 40 Mm were taken into account for the power-law approximation. This is due to the fact that the linear plot on integral dependences

¹ The article is published in the original.

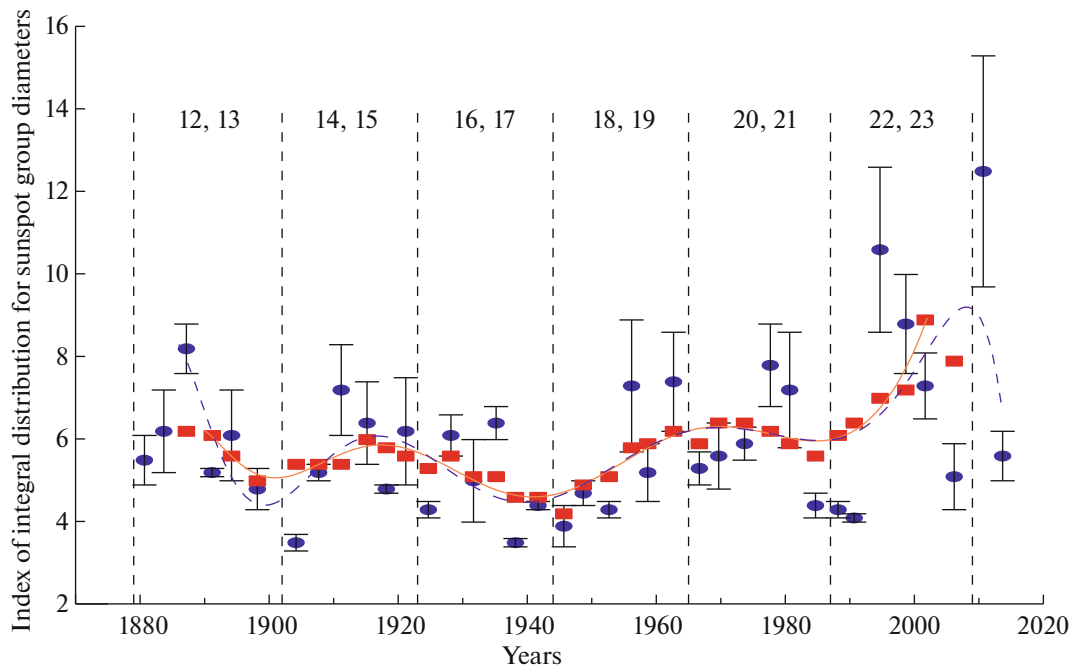


Fig. 1. The comparison of the α index found separately for the growth, maximum, and attenuation phases of each cycle. Vertical dashed lines show pairs of Hale cycles (even + odd cycles). A wavy solid and dashed lines present polynomial approximations (see text).

for sunspots (from which α index can be determined), is mostly within the range of 50–90 Mm (Babij et al., 2011).

3. RESULTS

We analyzed integral dependences of sunspot group diameters by the same method as in the above-named paper. In principle, the statistics of sunspots could be described by differential dependences, i.e. histograms showing the number of spots in a certain interval of their diameters. However, these dependencies require the introduction of several parameters to describe them. With limited observational statistics, not all these parameters could be determined with sufficient accuracy. Therefore, it is advisable to consider only one parameter, which accumulates the maximum number of observational data. This parameter is the index α for the power-law approximation in the formula $N \sim d_{\text{eqv}}^{-\alpha}$, where N is the number of elements (i) of a statistical ensemble with the parameters $d_i \geq d_{\text{eqv}}$. This actually means that every time we sum up the number of all elements falling to the abscissa region that is to the right of d_{eqv} value on the differential dependence.

Similar to paper by Babij et al. (2011), the α parameter was determined for sunspot group diameter range of 50–90 Mm. We found that this parameter, really, turn out to vary greatly inside any cycle and from cycle to cycle, in range about 4–12 units (Fig. 1). In this figure, the filled circles represent a value of α separately

for the growth phase, maximum and cycle extinction. For the 24th cycle, only two values are presented for the reason that this cycle is not yet complete. Errors in determining the parameter α were estimated by the degree of correspondence of observations in range 50–90 Mm to linear approximation. Comparing the empirical dependence with the linear approximation, we calculated the parameter α in two ways: for all five N values in the interval of 50–90 Mm, found with 10 Mm step, and also for only four ones, discarding those extreme points on integral dependences that deviate as much as possible from the linear approximation. The error in determining the parameter was estimated by the discrepancy between its values found with the two specified methods of calculating it.

The obtained empirical data were approximated by a polynomial of the 10th degree (the dashed wavy line in the figure). It is seen that, despite the large scatter of the points in the figure, the 44-year periodicity of changes in this parameter is quite well manifested. For greater clarity, in the figure the vertical dashed lines show the limits of the pairs of Hale cycles (even + odd). Here we also show the results of averaging the data by five points on the graph (filled squares); a solid line represents the approximation of these data by a polynomial of the 9th degree. This approximation only confirms the main tendency, i.e. the existence of 44-year-old variations whose minimums and maximums fall on the boundaries of 22-year Hale cycles.

The temporal distribution of maximum area of sunspot groups per year $S_{p,\text{max}}$ is presented in Fig. 2.

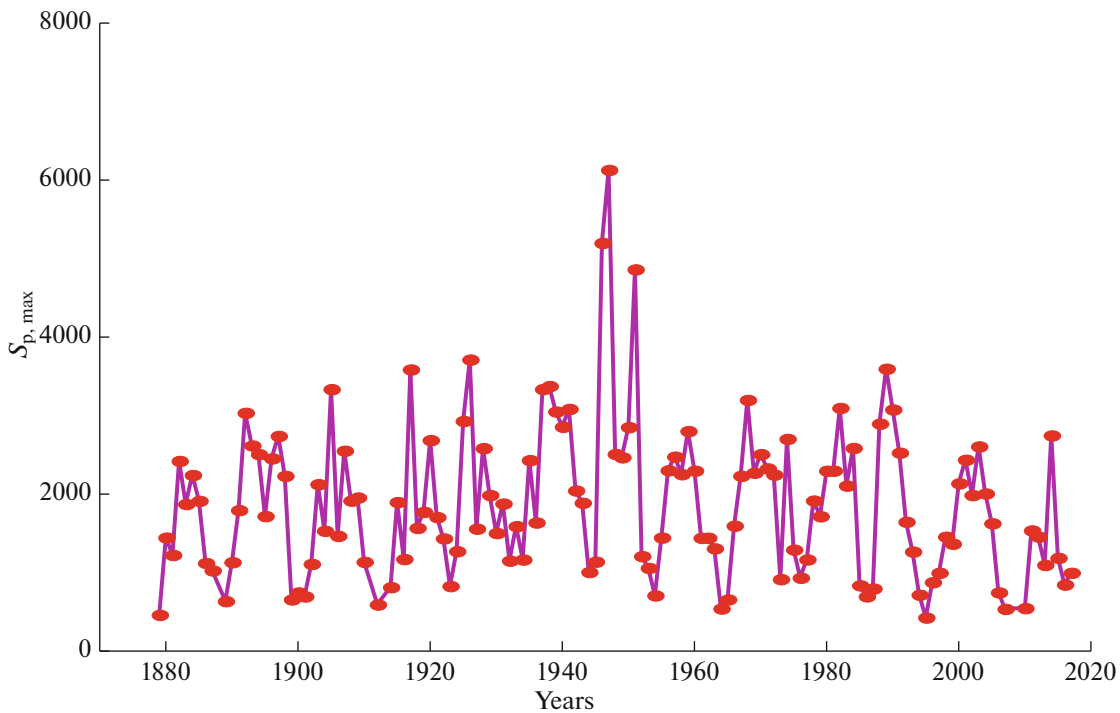


Fig. 2. The temporal variations of maximum area of sunspot groups per year. On the vertical axis the projection-corrected whole sunspot group areas are given in millionths of solar hemisphere ($1 \text{ m.s.h.} = 3.04 \times 10^6 \text{ km}^2$). One can see that a high and relatively short jump of $S_{p,\max}$ parameter was in the 18th cycle.

Data for 1879–2015 were borrowed from the Greenwich catalog, and preliminary data for 2016 and 2017 from the site www.solenn.info/solar/. One can see a remarkable feature in Fig. 2, namely, a sharp jump in the $S_{p,\max}$ parameter during 1946–1947 that appeared at the phase of growth and maximum of the 18th cycle. Another slightly weaker jump was in 1952, during the decay phase of the 18th cycle. It is interesting to note that these sharp jumps were not in the most powerful cycle no. 19, but in a somewhat weaker cycle no. 18. The peak values of $S_{p,\max}$ in Fig. 2 are as follows: 5202 (February 7, 1946), 6132 (April 8, 1947) and 4865 (May 19, 1951). According to formula $d_{\text{eqv}} \approx 2 (S_p)^{1/2}$, equivalent diameters d_{eqv} of sunspot group are 144, 157 and 139 Mm, respectively.

From Fig. 2 it can be seen that the 11-year cycle is also manifested here, but not so distinctly as in the numbers of the sunspots. With respect to the parameter $S_{p,\max}$, the 19th cycle is a modest cycle.

4. DISCUSSION

It is worth mentioning that the first indications of 44-year cycle of changes of Wolf numbers were obtained by Tsurulnik et al. (1997). However, this cycle has only a fifth rating after the cycles with the duration about 11, 12, 10 and 95 years (the order of cycles corresponds to the descending order of their capacity in a power spectrum). The assumption of the existence of

double Hale's cycle was also suggested by Javaraiah (2003) after studying speed of the differential rotation of Sun in different cycles. Perhaps, the 44-year cycle exists also in changes of magnetic fields in large sunspots. In particular, Lozitska and Efimenko (2015) reported the minimum magnetic field intensity in such sunspots in 1965 and in 2008–2009, i.e., having interval of 43–44 years. According to the data of authors mentioned above, the 11-year cycle is more obvious here. Pevtsov et al. (2011) also found deep minimum in magnitudes of sunspot magnetic fields in around 1965.

As can be seen from Fig. 1, 1965 corresponds to the beginning of the Hale's pair formed by cycles nos. 20 and 21. Accordingly, 2008–2009 should correspond to the beginning of the Hale's pair nos. 24 and 25. Thus, we can see an obvious evidence of definite relationship between the α index and the magnitude of the magnetic field intensity of sunspots.

Insofar as the value of α reflects the dispersion of diameters of sunspots, our data indicate that the convection zone generates solar active region embryos in various modes of statistics, which vary with the cycle of about 44 years. From this point of view, the 44-year cycle is a clean solar cycle, which is also reflected in the number of sunspots, the speed of sunspot rotation and the intensity of their magnetic field.

5. CONCLUSIONS

A revision of the results by Babij et al. (2011) on a base of the Greenwich catalog for the last 13 solar cycles shows the following: (a) significant fluctuations in the power-law index on integral dependences for the diameters of sunspot groups are confirmed, but there is no clear its dependence on the phase of the cycle, (b) there are 44-year-old oscillations of the power-law index corresponding to double Hale's cycle for changing the polarity of the magnetic fields of sunspots and (c) we confirm the unique sporadic phenomenon – a sharp jump in the maximum diameter of sunspot groups in 1946–1947, however, we did not find such leap in 1939 by the Greenwich catalog.

ACKNOWLEDGMENTS

This study was funded by the Taras Shevchenko National University of Kyiv, project no. 16БФ023-01.

REFERENCES

- Babij, V.P., Efimenko, V.M., and Lozitsky, V.G., Statistical characteristics of large sunspots in solar activity cycles 17–23, *Kinematics Phys. Celestial Bodies*, 2011, vol. 27, no. 4, pp. 191–196.
- Efimenko, V. and Lozitsky, V., Statistical peculiarities of 24th cycle of solar activity, *Bull. Kyiv. Nats. Univ., Astron.*, 2016, no. 53, pp. 52–55.
- Gnevyshev, M.N., Essential features of the 11-year solar cycle, *Sol. Phys.*, 1977, vol. 51, pp. 175–183.
- Hale, G.E. and Nicholson, S.B., The law of sun-spot polarity, *Astrophys. J.*, 1925, vol. 62, pp. 270–300.
- Javaraiah, J., Long-term variations in the solar different rotation, *Sol. Phys.*, 2003, vol. 212, no. 1, pp. 23–49.
- Krivova, N.A. and Solanki, S.K., The 1.3-year and 156-day periodicities in sunspot data: Wavelet analysis suggests a common origin, *Astron. Astrophys.*, 2002, vol. 394, pp. 701–706.
- Lean, J.L. and Brueckner, G.E., Intermediate-term solar periodicities: 100–500 days, *Astrophys. J.*, 1989, vol. 337, no. 1, pp. 568–578.
- Lozitska, N.I., Problem of mistakes in databases, processing and interpretation of observations of the sun, *Odessa Astron. Publ.*, 2015, vol. 28, no. 2, pp. 236–237.
- Lozitska, N.I. and Efimenko, V.M., Indexes of groups of sunspots for long-term forecasting of geomagnetic activity, *Byull. Kyiv. Natl. Univ., Astron.*, 2015, no. 52, pp. 43–47.
- Mandal, S. and Banerjee, D., Sunspot sizes and the solar cycle: analysis using Kodaikanal white-light digitized data, *Astrophys. J. Lett.*, 2016, vol. 830, no. 2, id L33.
- Muñoz-Jaramillo, A., Senkpeil, R.R., Windmueller, J.C., Amouzou, E.C., Longcope, D.W., Tlatov, A.G., Nagovitsyn, Y.A., Pevtsov, A.A., et al., Small-scale and global dynamos and the area and flux distributions of active regions, sunspot groups and sunspots: A multi-database study, *Astrophys. J.*, 2015, vol. 800, no. 1, id 48.
- Nagovitsyn, Yu.A. and Pevtsov, A.A., On the presence of two populations of sunspots, *Astrophys. J.*, 2016, vol. 833, no. 1, id 94.
- Pevtsov, A.A., Nagovitsyn, Yu.A., Tlatov, A.G., and Rybak, A.L., Long-term trends in sunspot magnetic fields, *Astrophys. J. Lett.*, 2011, vol. 742, no. 2, id L36.
- Svalgaard, L., Cliver, E.W., and Kamide, Y., Sunspot cycle 24: Smallest cycle in 100 years?, *Geophys. Res. Lett.*, 2005, vol. 32, no. 1, L01104.
- Tsirulnik, L.B., Kuznetsova, T.V., and Oraevsky, V.N., Forecasting the 23rd and 24th solar cycles on the basis of MGM spectrum, *Adv. Space Res.*, 1997, vol. 20, no. 12, pp. 2369–2372.