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On development of a new index of solar activity

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Abstract. A new procedure has been developed to determine a new index *In* of solar activity (SA), which is convenient for prompt warning the nationality about the state of SA through the means of public information (MPI) by using a 10-level scale on which the largest value corresponds to the period of the highest activity of the Sun at the maximum of its 11-year cycle. The methodology is based on the known properties of the universally adopted indices of SA and implemented through radio observations of the Sun with high spatial resolution in the range (4–6) cm. The results are presented of testing this procedure for the year-long period of observations (1981) and also the results of utilization of this procedure in real time in the Russian TNT TV programme "Solar forecast" in April–December, 2001. The procedure proposed is sufficient to record the passage of the largest active regions ($S_p > 5000 \cdot 10^{-6} hemi$) across the disk of the Sun, when the flare activity increases and therefore does SA geoefficiency. In contrast to the universally accepted indices, the new SA index registers not the number of active regions or the intensity of their integral radio emission, but characterizes the power of individual active regions that are present on the disk of the Sun at a given moment.

Key words: Sun: activity — Sun: radio emission — sunspots

1. Introduction

The International Relative Numbers of sunspots (W), the so-called Wolf numbers (Wolf, 1860–1866) are the universally accepted index of solar activity (SA). They are well correlated with the integral radio emission flux from the Sun at a wavelength of 10.7 cm ($F_{10.7}$) which is now frequently used as an independent index of SA on an equal footing with the Wolf numbers. Both these indices register the integral characteristics of SA: the Wolf numbers W are used for recording the number of active regions (AR) and individual spots, while $F_{10.7}$ for the intensity of the total radio emission of a quiet Sun and of all the sources of the S-component (local sources) found on the disk. From the point of view of the two indices, the rise in SA associated with one, but large AR, or with a collection of smaller AR can hardly be distinguishable. However, the difference is quite essential for determination of geoefficiency of SA, for it is known that intense flares and coronal mass ejections occur most frequently in large AR.

The influence of SA on the terrestrial life (German et al., 1981) is so great that man has to know its state as well as the weather forecast. The development of the means of public information (MPI) makes it currently possible to inform a wide audience of the situation. It is necessary that this information should be comprehensible to people having no astronomical education. Considering this, we have stated a problem to develope a ten-level scale for estimate of the level of SA, which could be easily comprehended by analogy with the Richter scale for earthquakes.

2. Algorithm of the new index and its realization

The proposed scale is intended for giving a knowledge of the phase of the 11-year cycle of SA, how the level of SA differs from the minimum value for the given phase and what the power of AR occurring on the solar disk at the given moment is.

The scale of evaluation of the level of SA that we propose is based on the laws which can be derived from analysis of a series of W and $F_{10.7}$ (as well as from any other flux series at shorter wavelengths, since in the range (4.0–11) cm they correlate well enough with one another, see Fig. 4). A series of W over the last 4 cycles, beginning with the 19th one, is presented in Fig. 1. It is seen that this curve can be divided into two components: (1) a lower envelope — the recurrent part (shown with the dotted line)

Table 1: *The variable component of the SA index In^V*

$F_{l.s.}^{max}$, s.f.u.	$In^V(L<0)$	$In^V(L>0)$
$F_{l.s.}^{max} < 10$	0	0
$10 \leq F_{l.s.}^{max} < 15$	1	1+1=2
$15 \leq F_{l.s.}^{max} < 30$	2	2+1=3
$30 \leq F_{l.s.}^{max} < 50$	3	3+1=4
$F_{l.s.}^{max} \geq 50$	4	4+1=5

Notes: $F_{l.s.}^{max}$ means the flux value of the most intense local source of S-component of solar emission at (4–6) cm at a given moment in solar flux units ($1s.f.u. = 10^{-22} W/m^2 Hz$). L is the longitude from the CM of the Sun

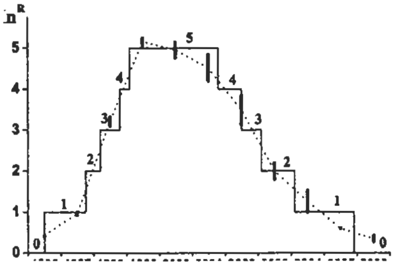

Figure 2: *The shape of the recurrent component of the index In^R for any 11-year cycle of the Sun.*

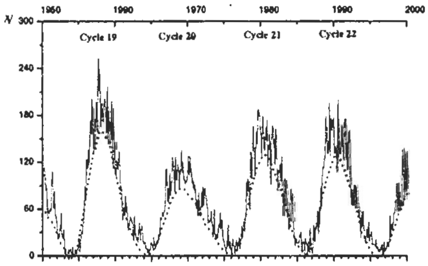

Figure 1: *Wolf numbers W. The lower envelope (dotted line) divides the recurrent and variable component of this series by the example of four solar cycles.*

and (2) a variable component. The latter is related to the moment of particular increasing of SA during the period of passage of individual centres of activity or their complexes across the disk of the Sun. The origin of the recurrent part is due to smaller structures, the number of which increases at the maximum of each 11-year cycle of SA. The averaged shape of the lower envelope for a single cycle over (8–22) cycles of SA is well known (Solar Geophys. data, 2001). While developing the scale of the SA level, we modeled it as the mean for 21 and 22 cycles of SA the intensity of which proved to be equal. This curve is shown in Fig. 2.

With accounting the characteristic features of the above indicated series of W and F, the index of SA that we introduce is suggested to be divided into two components:

$$In = In^R + In^V,$$

where In^R is the recurrent part, and In^V is the variable part. The maximum value of In is 10 levels. Five values out of 10 refer to the recurrent part (see Fig. 2). Thus, the recurrent part In^R is calculated for the whole current cycle (23rd) of SA and may be assumed as a basis for all subsequent cycles. What are the reasons for such scale normalizing and how can In^V be determined?

The answer to these question is contained in the results of long-time investigations of radio emission of the active Sun carried out with high spatial resolution with BPR and RATAN-600 (Gelfreikh et al., 1970; Bogod, 1995) and also with small mirrors, in particular RT-3 (Cuba, IGA) (Gelfreikh et al., 1974). The analysis of observations of the integral flux of emission from the Sun ($F_{4,5}$) at 4.5 cm over nearly three latest cycles (beginning with 1969) has shown that during the maxima of the cycles (1968–1970; 1980–1982; 1989–1991) the fluxes differ by about a factor of two ($F_{\odot}^{min}$ and $F_{\odot}^{max}$ are $\sim$ 200 s.f.u. and $\sim$ 375 s.f.u., respectively). The 10-level scale of In was shared in the same proportion between In^R and In^V. Five levels were allotted to the latter, with the help of which one can estimate In^V in accordance with the rules presented in Table 1. It follows from Table 1 that the value of In^V is suggested to be estimated from the radio emission of the centre of activity region predominant on the disk of the Sun at the given moment. An increase in In^V at $L > 0$ by 1 level takes account of the geoefficiency increase of the centre of activity in passing to the western hemisphere of the Sun. Thus, the proposed procedure of determination of In^V relies on observations with high spatial resolution (not worse than 1–3 arcmin), which makes it possible to separate radiation of an individual AR. The difficulties in separation which arise in one-dimensional observations (BPR, RATAN-600) can be avoided through the involvement of data on the areas of solar spots (S_p). It is known (Peterova, 1974) that in the range (4–6) cm the flux of the local source $F_{l.s.}(s.f.u.) = (2 \div 3)S_p/100$, where S_p is given in $10^{-6} hemi$ ($hemi = 2\pi R_{\odot}^2$). This relationship permits the sources falling simultaneously within the vertical beam pattern of BPR or RATAN-600 to

Table 2: *Determination of the current value of In illustrated by the observations during the period of high activity of the Sun in 2001*

Date	August 2001				September 2001			
	28	29	30	31	02	03	05	06
No. AR	9591	9591	9591	9591	9601	9601	9601	9601
L	-6	6	22	33	-18	-8	22	38
In^R	5	5	5	5	5	5	5	5
$F^{max}_{l.s.}$, s.f.u.	36	46	26	26	30	50	50	52
In^V	4	4	3	3	3	4	5	5
$In = In^R + In^V$	9	9	8	8	8	9	10	10

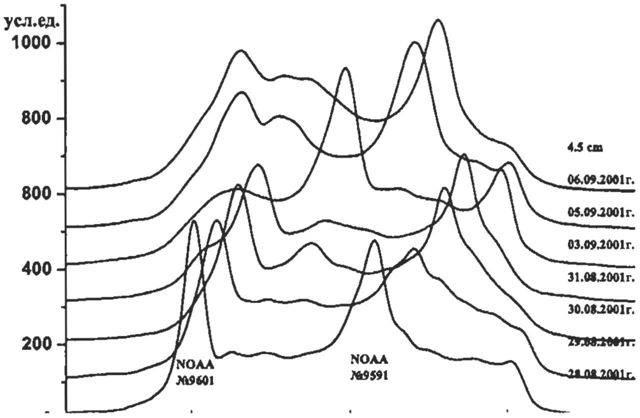

Figure 3: *An example of observational data for the determination of the index In (BPR scans of the Sun).*

be separated.

As indicated above, only four levels are allotted to the variable part of the index In^V, by means of which the intensity of radio emission is estimated in very wide limits: from 10 to 100 $s.f.u.$ From this it follows that a one-level step in In^V is a rather significant event. An AR falling within the first class by its parameters, which is characterized by $In^V = 1$, is already quite a large structure on the disk of the Sun ($S_p \approx 500 \cdot 10^{-6} hemi$). $F_{l.s.} = 10 s.f.u.$ at $\lambda = 3$ cm is a lower limit of the Tanaki-Enome criterion, this is why, it can be expected that an AR of such an intensity will be a source of proton events. During the period of the maximum of the solar cycle, ARs of such an intensity arise very frequently, and there may be several of them at the same time. The class characterized by $In^V = 2$ is much less frequent ($S_p \approx 1000 \cdot 10^{-6} hemi$), $In^V = 3$ and especially $In^V = 4$ ($S_p \approx 2000 \cdot 10^{-6} hemi$) are but isolated events.

We will show by a specific example how the proposed procedure of estimation of In can be applied. For illustration we have chosen the 2001 August-September period of observations. According to the diagram in Fig. 2, $In^R = 5$ for this period. We present in Fig. 3 a sequence of scans obtained in the observation of the Sun with BPR at the wavelength 4.5 cm. One can see that the sources identified with the ARs NOAA 9591 and NOAA 9601 were predominant in intensity sources of S-components in the given period. By using the technique of reduction of scans obtained with BPR (or RATAN-600) (Borovik et al., 1987; Garaimov, 1997) determine the flux of radio emission from these sources, $F^{max}_{l.s.}$, and analyse its value according to Table 1. The final results of this analysis are collected in Table 2.

The level of SA during this period is seen to reach maximum values and exceeded the recurrent level by 3–5 steps. The two groups of spots had a comparatively small area, $S_p \sim (700 - 800) \cdot 10^{-6} hemi$, but were of increased radio brightness.

The procedure of determining the level of SA proposed here was tested by the data of observations of the Sun during one year (1981), and its results were compared with the well-known accepted indices of SA (W and $F_{10.7}$). A period near the maximum of the 21st cycle of SA, when the magnetic field of the Sun was at the same phase as now, was used for the comparison. The already reduced scans of the Sun obtained with BPR and published in the bulletin "Solar data" (Solar data, 1981) were used as the observational data. The results of the comparison are shown in Fig. 4 and Table 3, where, apart from In, $In*$ is also given which does not contain the correction for the longitude of the AR which inhibits comparison with other indices of SA taking no account of geo-efficiency of SA. The correlation of In with W and $F_{10.7}$ is seen to be rather low, the same as with $F_{4.5}$ obtained at the same wavelength, 4.5 cm, at which In was chiefly determined. This is the expected result because W, $F_{10.7}$ and $F_{4.5}$ are integral quantities, while In is estimated from the intensity of the predominating AR. ¿From the point of view of In, the period of maximum phase in the 21st cycle of SA (1981) can be characterized with the aid of the histogram shown in Fig. 5. From the analysis of this histogram it follows that the activity on the whole was rather high: over 60 % of time, ARs whose intensity of radio emission was within (10–30) *s.f.u.* were present on the disk of the Sun. Note that an increase in In of up to (8–9) levels registers the moments poorly detectable in W and $F_{10.7}$. For instance, here belong individual periods in 1981 March and April, indicated by arrows in Fig. 4. They turned out to be related to a sharp rise in activity and change in the structure of ARs which at first had a small area, $\sim 300 \cdot 10^{-6} hemi$. This process was accompanied by an increase in intensity of radio emission of the ARs HR 17512 (CD110 — March 1981) and HR 17590 (CD177 — April 1981). On the other hand, another two cases of increase in In (July and October) do fall within the period of passage of several large ARs with an area of $\sim 2000 \cdot 10^{-6} hemi$ across the disk of the Sun at the same time, which is well noticeable in $F_{10.7}$ and $F_{4.5}$.

3. Characteristic properties of radio emission of bright ARs

As it follows from the above-stated, the index of SA that we propose reflects the contributions of ARs of large area and ARs of increased radio brightness to the total level of solar activity. The latter are of interest from the point of view of the common problem of heating the active corona. As an illustration, we consider 4 ARs the main characteristic properties of which are collected in Table 4.

The 4 ARs presented in Table 4 had a complex and variable magnetic field structure. The maximum

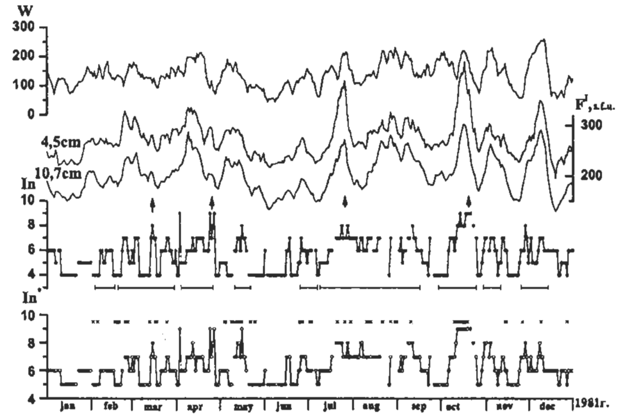

Figure 4: *Comparison of the indices In and In* with other indices of SA. The symbol (-) designates the periods, when the area of the largest spot on the Sun is* $S_p > 500 \cdot 10^{-6} hemi$. *The flares of class > 2B are marked by the crosses.*

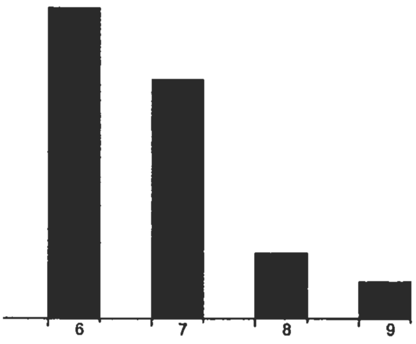

Figure 5: *A histogram of the distribution of the index In for a year-long period of time (1981).*

Table 4: *Characteristics of ARs for bright local sources*

No. AR from SGD	CMP	Morphological class	S_p $\cdot 10^{-6} hemi$	$F/S_p \cdot 10^{-2}$ s.f.u.$/10^{-6} hemi$	Notes
HR 17512	1981 III–12	E	750	2–5	Activization of AR, enlargement of spots
HR 17590	1981 IV–20	D	1000	2–6	Formation of a penumbra of large area
NOAA 9591	2001 VIII–28	F	650	5–7	Long-lived δ-configuration of the magnetic field in the trailer spot
NOAA 9601	2001 IX–03	E-F	750	4–7	Multicentral compact AR

Notes: CMP — the moment when the active region passes through the central meridian, SGD — Solar Geophysical Data (international journal).

Table 3: *The coefficient of correlation between different indices of SA*

Series	Correl. coeff.
W–$F_{10.7}$	0,84
W–$F_{4.5}$	0.71
W–In^*	0.36
$F_{10.7}$–$F_{4.5}$	0.90
$F_{10.7}$–In^*	0.58
$F_{4.5}$–In^*	0.66

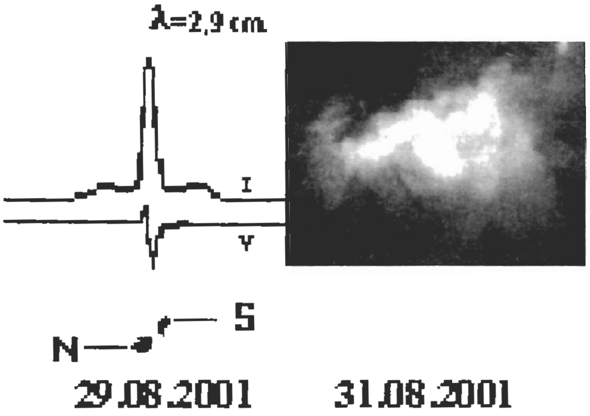

Figure 6: *RATAN-600 scans of the bright AR NOAA 9591. A photogeliogram data are also shown.*

radio brightness of these ARs, the measure of which is the radiation capacity F/S_p, exceeds the average statistical one for ARs of morphological class D-E-F (Peterova, 1974) by a factor of 3–4. There are different scenarios of corona heating above an active region many of which are associated with flare activity. However, the activity may also show up in the form of coronal mass ejections of flare-like streamers (Peterova et al., 2001a). The most remarkable is the case of the bright AR NOAA 9591, in which no intense flares occurred. Fig. 6 displays a scan of the AR at 2.3 cm from RATAN-600 observations in intensity I and radio emission circular polarization V.

The source of heating the corona in this AR was the energy of a nonpotential magnetic field which was released in the region of a quasistationary coronal arch of increased brightness (see Fig. 6), having the footpoints rooted in the nuclei of spots of different polarity.

The radio brightness is a parameter that can form a foundation for classification of ARs without duplicating those already available (morphological, magnetic, etc.). The results of the present paper suggest that the brightness of ARs is independent of the area, morphological class of the corresponding group of spots and magnetic field strength. The brightness estimate of the whole AR (its upper limit) can easily be made by measuring the radiation capacity, which is accessible to observations even with moderate spatial resolution. This approach was already applied when developing the method of classification of ARs on the basis of structural characteristic features of radio emission (Peterova et al., 2001b) with the only difference that there we used the brightness of the sunspot component of the local sources. The radio range is much more sensitive to temperature than the X-ray range, and this is its main advantage in studying the problem of active solar corona heating.

4. Discussion of results

The Wolf numbers are the most familiar index of SA despite the fact that W (the measure of "spottedness" of the solar disk by the definition of Wolf) has no physical sense.

$$W = 10g + f,$$

where g is the number of groups of spots, f is the number of spots. It is remarkable that there is good correlation between W and $F_{10.7}$, that is, the artificially composed number W represents nearly exactly how the intensity of radio emission of the active Sun changes, quite a definite physical quantity, which represents the degree of coronal plasma heating. This can be explained on the basis of the results of investigations of sources of the S-component of solar radio emission, a particular place in which is taken by the study of the structure of these sources carried out from observations at RATAN-600 (Akhmedov et al., 1986; Peterova, 1994). According to these studies, the relationship between the contribution to the emission of an individual local source of the sunspot component and the magnetosphere of the given AR depends on wavelength. With increasing the wavelength (by $\lambda > 5$ cm) the radiation of the plasma held at the top of the coronal loop (AR magnetosphere) begins to predominate, while the contrast of the sunspot sources located below considerably decreases. Thus, the main role comes to be played by the fact whether the spots are united in a group, but not by their number. It is precisely Wolf's reasoning: in his formula for W the weight coefficient at g is an order of magnitude larger than at f (Wolf, 1860–1866)). It seems to us that the most "physical" index that fully represents the energetics of an AR is the integral solar emission flux F in the range (4–6) cm. At these wavelengths both main components of the local source structure are observed with a sufficient contrast: sunspot details of the cyclotron radiation source in strong magnetic fields and the "halo" identified with the top of the coronal loop. The sunspot component is much more variable as compared to the halo and represents better the dynamical processes going on in AR and most likely related to the magnetic field variations. Because of this, the index of activity, understood as F_{4-6}, can be recommended for fundamental investigations of the solar-terrestrial relations. It should be noted that a correlation has recently been found between the repeated inversions of the sign of circular polarization of AR radiation in the range 2–5 cm and the flare activity (Tokhchukova and Bogod, 2002). These processes point to the existence of reconstruction in the height structure of the underlying magnetic field layers prior to powerful flares and also demonstrate the efficiency of microwave studies of flare-productive active regions on the Sun.

The index of SA that we propose in this paper is intended first of all for evaluation of geoefficiency of SA and prompt notification of people about its level. However, as one can see from the stated above, when developing the index, maximum use of the physically significant parameters of solar radiation was made. What are the main properties of the new index of SA, its merits and demerits?

1. The scale of SA level estimation that we have introduced is relative: in contrast to W and $F_{10.7}$, the series of In will be a sequence of cycles of equal amplitude. This kind of simplification is intended exclusively for publication of data on the level of SA in MPI: these must be quantitative and easily remembered. The developed procedure is designed for fast transfer of data to the user, that is, for operation under the condition of express-information and cannot therefore claim to be of high accuracy.

2. Within a time interval of ~ 11 years, In must represent well the cyclic variation of SA, for the recurrent part of In^R is, by definition, a strongly smoothed value of the W numbers. One may expect that the correlation between In and W in the cycle will be much higher than that derived in the analysis of the year's cycle.

3. The most remarkable part of the procedure is the calculation of the variable component of the index In^V, which, as distinct from W and $F_{10.7}$, allows judging not of the number of ARs but of their intensity. The contribution of In^V to the total value of the index must increase on the descending branch of the solar cycle, when the number of large ARs generally rises, while In^R will decrease.

The main simplification which was used at the first stage of development of the SA index is the evaluation of the SA level on the basis of reduction of observations of only one AR dominating on the solar disk in the given period, although in actual fact they can sometimes be more numerous. Subsequently, with accumulation of experience of working by this method, it may prove to be possible to explore not one but all large ARs on the Sun at the given moment by means of certain elaboration of the procedure. One should expect an improvement in correlation between In and the already recognized indices of SA, W and $F_{10.7}$.

5. Main results

1. A procedure for determination of a simplified index of SA, specially for MPI, is developed which gives an idea of the phase of the 11-year cycle (max and min) at which the Sun is and of how much the level of activity differs from the maximum value for the given phase.

2. The main distinguishing feature of the proposed index, in contrast to the already known Wolf numbers (W) and the radio emission flux at 10.7 cm ($F_{10.7}$), is the introduction of a 10-level scale of SA level estimation, which is independent of the power of the current cycle of SA. This approach does not require a special knowledge in using this index and gives people a quantitative idea of how dangerous the Sun is at a given moment.

3. The properties of the well-known accepted indices of SA, W and $F_{10.7}$, and the data on the charac-

teristic properties of the sources of the S-component of radio solar emission derived in observations with high spatial resolution form the foundation of the scale of evaluation of the SA level that we propose.

4. An evaluation test of the method by way of twelve months' observations of the Sun has shown that the new index of SA registers quite well the moments when a large group of spots ($S_p > 500 \cdot 10^{-6} hemi$) is present on the Sun, and the number of flares and bursts, as well as their intensity, increases. The technique has found application on television in a part of the TNT programme "Solar forecast" in 2001 April-December.

5. To carry out fundamental research, it is recommended to use, as the index of SA, the integral solar emission flux in the range (4–6) cm as one having a certain physical sense and representing to the utmost the degree of active corona heating in a wide interval of heights — from several thousand kilometers to hundreds of thousand kilometers above the photosphere, and therefore characterizing the activity of processes responsible for the coronal plasma heating.

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