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ESAI DATABASE AND SOME PROPERTIES OF SOLAR ACTIVITY IN THE PAST

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Abstract. In this work a new information resource located at *http://www.gao.spb.ru/database/esai* and hereinafter referred to as ESAI ("Extended time series of Solar Activity Indices") is presented. ESAI includes observational, synthetic and simulated sets to study solar magnetic field variations and their influence on the Earth. ESAI extends the ordinary lengths of some traditional indices, parameterizing time variations of physically different characteristics of solar activity. In particular, long-term sets of the following indices are presented: sunspot areas, the Wolf numbers, polar faculae numbers, sunspot mean latitudes and north-south asymmetry of hemispheres for different components of activity. Some methods for making correct conclusions from incomplete data and some criteria to estimate the reliability of the obtained information are discussed.

1. Introduction

One of the most attractive problems in modern Earth-oriented sciences is the search for causes of the long-term climatic changes. As is shown in a number of investigations, some part of these changes is caused by influence of solar activity as an external factor. For the study of the long-term solar-climatic links as well as the solar activity process *per se* we should have representative observational data. However, we lack in-depth data on "the history of the Sun" even for relatively short (centennial and multi-centennial) periods, not to mention the deficiency of reliable information for longer (millennial or multi-millennial) time scales. In this work the prolonged time series of various indices of solar activity (SA) are presented and some questions on studying of long-term behaviour of the solar activity are discussed. In particular, we shall be interested in the following: (a) Construction of homogeneous time series of solar activity indices; (b) Methods to make correct conclusions from incomplete data; (c) Estimating the confidence of the obtained data. We shall also mention some properties of solar activity that seems obvious from the data obtained by us.

2. ESAI Database and Time Series Based on Direct Observations

"Extended time series of Solar Activity Indices" (ESAI) is a database that is sited at *http://www.gao.spb.ru/database/esai* and includes observational, synthetic and simulated sets to study variations of solar magnetic fields and their influence on the Earth. ESAI extends in time the ordinary lengths of some traditional indices: the sunspot areas, the Wolf numbers (the equatorial component of the magnetic field of the Sun), the polar faculae numbers (the polar component of the field), the mean sunspot latitudes, the north-south asymmetry of hemispheres (location of the activity) in terms of the standard observational systems (Greenwich, Zürich-International, etc.). Thus, ESAI can be applied to the description of time variations of different characteristics of the solar magnetic field.

2.1. HOMOGENEOUS SERIES OF TOTAL SUNSPOT AREAS SINCE 1821

The total sunspot area index $A(t)$ is an important characteristic of solar activity variations because it is closely associated with the low-latitude magnetic flux. Unfortunately, regular observations of this parameter have started as late as in 1874 (Royal Greenwich observatory) and only their 130 year set is available. For comparison, two other sets that parameterize sunspot activity cover 300 year (Wolf number $W(t)$) and 400 year (Group Sunspot Number $GSN(t)$) time intervals. However, that latter sets are not so physically obvious as the summarized sunspot area index.

In 1870 De la Rue, Steward, and Loewy (1870) compiled a series of sunspot areas using drawings and early photographs of the Sun in the period 1832–1868. Those data include the observations by Schwabe for the period 1832–1853, by Carrington, 1854–1860, and De la Rue's own records carried out at Kew observatory, 1862–1868.

Recently, Vaquero, Callego, and Sanches-Bajo (2004) have proposed a simple procedure to merge the Greenwich and De la Rue's series using two global linear regressions $A(t) = m_1 W(t) + n_1$ and $A(t) = m_2 GSN(t) + n_2$. We shall notice, however, that in the strict sense the sunspot areas and both W and GSN are physically different quantities. That was the reason why in the older work (Nagovitsyn, 1997a) a more refined procedure was proposed. Namely, on the basis of sets of regressions $A(t) = m(\varphi)W(t) + n(\varphi)$ (where φ is the phase of the 11-yr cycle) derived for the time interval since 1874, with use of Wolf numbers for period before 1874, the auxiliary simulated series of sunspot areas $A_W(t)$ were initially calculated. Then, separate time segments of these series, as short as 15 years (because of probable dependence of the regression coefficients on phase of longer cycles than the 11-year one), were used for consecutive linear merging of three parts of the De la Rue records. Final reduction of early sunspot area observations to the Greenwich general system and filling of the gaps were made using separate time parts of $A_W(t)$. Finally, the period after 1976 was filled with use of the sunspot area data from the Pulkovo catalogue of solar activity (Gnevysheva, 1994). In Figure 1 we can see that the ESAI-extension occupies a reasonable part of the total duration of the homogeneous series of the sunspot areas.

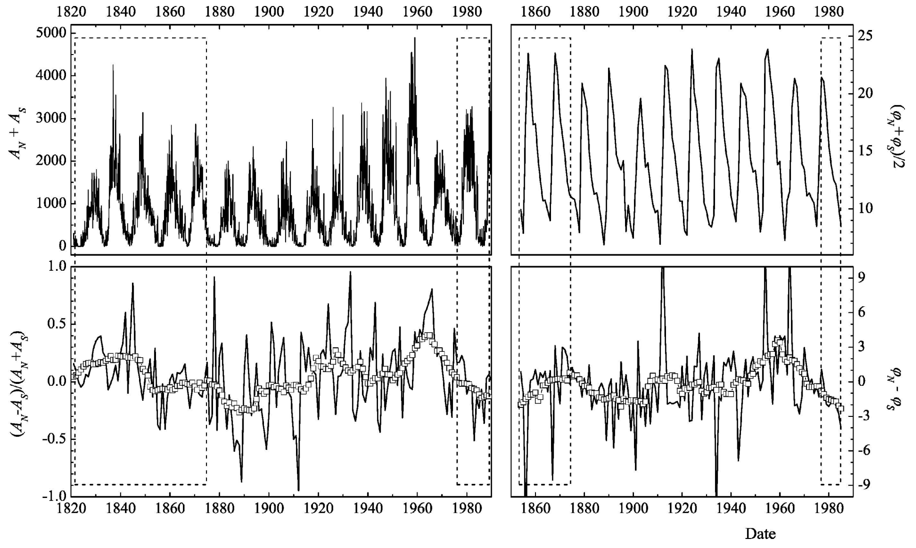

Figure 1. Left panels: long-time variations of the low-latitudinal magnetic flux: the monthly mean of the total sunspot areas (*upper*) and the north–south asymmetry of this parameter (*bottom*). *Right panels:* the yearly mean sunspot latitude index (*upper*) and its difference between N-S hemispheres (*bottom*). Here and below the ESAI extensions of solar activity indices are marked by the dotted rectangular borders.

2.2. SETS OF YEARLY NORTH–SOUTH ASYMMETRY OF HEMISPHERES SINCE 1826 AND SUNSPOT MEAN LATITUDES SINCE 1854

The north-south asymmetry index $q_A = (A_N - A_S)/(A_N + A_S)$ is an important, but still poorly known characteristic of variations of spatial distribution of the sunspot activity relative to the solar equator. Usually researchers use these series based on the Greenwich data, i.e. since 1874 (Carbonell, Oliver, and Ballester, 1993). To build the advanced homogeneous set of $q_A(t)$ we used Spörer (1861–1893), Carrington (1854–1860) and Newton and Milsom (since 1826) observational data (Nagovitsyn, 1997a).

Another important characteristic is the mean latitude of the zone of sunspot formation. Spörer has established that in the beginning of a 11-year cycle it is maximal, and then monotonically decreases. It would be interesting to clarify how this variation depends on the phase not only of the 11-year, but of longer cycles too – see Figure 1.

2.3. A SYNTHETIC SERIES OF POLAR FACULAE NUMBERS SINCE 1847

The faculae located in polar zones of the Sun are unusual phenomena of solar activity. It is enough to note that their 11-year cycle develops in antiphase with the sunspot one. Discovered by Weber in the middle of the 19th century, this phenomenon did

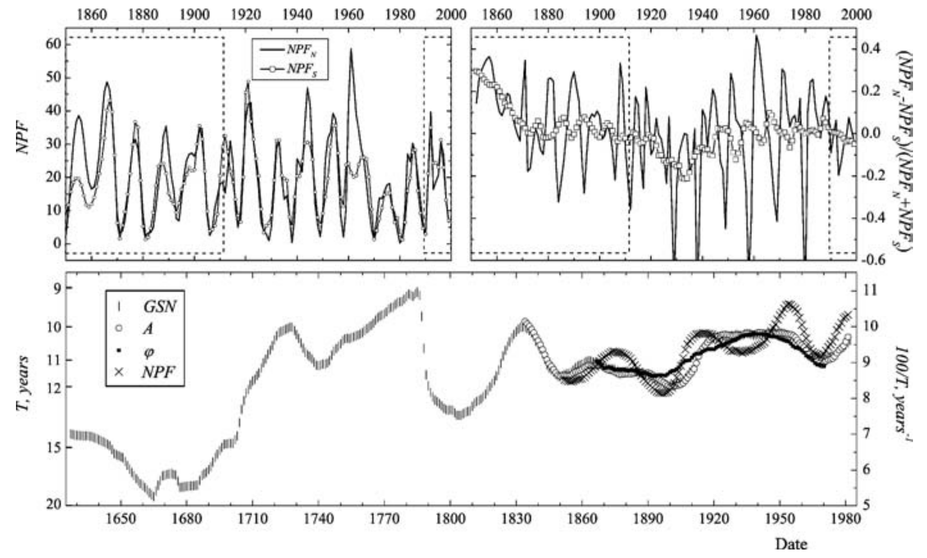

Figure 2. Upper panels: synthetic set of polar faculae numbers (*left*) end its N-S asymmetry of hemispheres (*right*). *Bottom panel:* variations of the 11-year cycle length for different indices of equatorial and polar components of solar magnetic field.

not attract attention of researchers for long. However, now it seems possible that they can play a leading role in an understanding of the mechanism of cyclicity (Makarov and Makarova, 1996). The long series of polar faculae were elaborated by Sheeley (1991) who used the Mt. Wilson data. The "synthetic" series of yearly polar faculae numbers presented in ESAI (see Figure 2) were constructed by combination of different data series: Mt. Wilson, Greenwich, Lyon, Kodaikanal, Tokyo, Zürich, Kislovodsk observations of the polar faculae and records (photographs, drawings) of polar coronal structures during solar eclipses (Nagovitsyn, 1988).

On the bottom panel in Figure 2 are shown the variations of the 11-year length derived from different ESAI sets with using a wavelet approach. We can see that the duration of 11-year cycle as a parameter of oscillatory process is a universal quantity for different indices of the global magnetic field of the Sun. Besides we shall notice that 11-year cycle monotonically grows in period T during the Maunder minimum, reaching $T = 18$–19 year values. We assume that it is the same Schwabe cycle rather than the Gnevyshev–Ohl cycle.

3. ESAI Database and SA Over Millennial Time Scale

3.1. SOLAR PATROL IN ANCIENT AND MEDIEVAL CHINA

Our approach to the naked-eye sunspot observations (mainly Chinese) is the ranking of each observation based on the nature of the data presented in the record

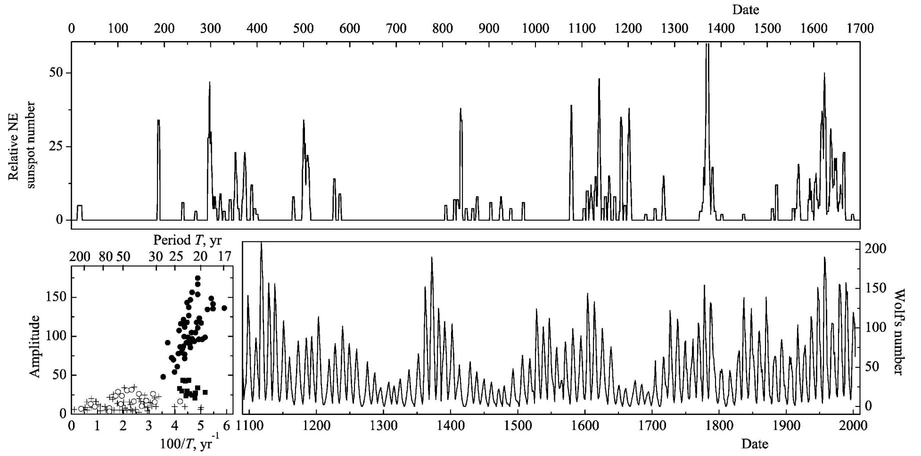

Figure 3. *Upper panel:* relative naked-eye sunspot number derived from Wittman and Xu catalog (1987). *Bottom panels:* amplitude *vs* frequency relationship for alternating-sign series $W(t)$ (*left*), and simulated yearly mean Wolf number since 1090 (*right*).

(Wittman and Xu catalog, 1987). We assign score 10 to the features called “moles” (in English translation) and score 15 to those called “spots” or “dots”. Scores 20 or 30 are prescribed to events whose descriptions are followed by phrases like “as large as a plume” or “...peach” (20) and “...melon” (30). We thus assume that every attempt of the observer to compare a particular spot with a familiar object is due to the especially large size of the feature in question. If the features observed on the Sun are compared to birds (“flying swallow,” “three-legged magpie”, etc.), it implies, in our opinion, the presence of several sunspot groups, each containing few visible spots. Finally, we took into account the duration of observation of the event. By this means a relative naked-eye sunspot number set was introduced (Nagovitsyn, 2001) – see Figure 3.

3.2. SIMULATED YEARLY MEAN WOLF NUMBERS SINCE 1090

The well-known problem of the search for relationships between duration of the 11-year cycle and its amplitude (Waldmeier, 1935; Hathaway, Wilson, and Reichmann, 2002) can be generalized within the framework of the approach of nonlinear oscillations and, in particular, of the Krylov–Bogolyubov approach. On the basis of this approach to the description of weakly nonlinear oscillatory processes, the nonstationary frequency-amplitude (f *vs* A) structure of the Wolf numbers (1700–1995) was analyzed. Using the nonlinear description f *vs* A and the well-known Schove’s data on the epochs of extrema of the 11-year solar cycles in the past, the yearly average Wolf numbers in 1090–1699 were reconstructed (more comprehensively, see Nagovitsyn, 1997b). Bearing both the 900-year duration and 1-year sampling of this series (see Figure 3) in mind, one can recognize that it is the unique time set of solar activity.

4. Methods of Attack against the Long-Term Sun

In view of the peculiarity of the problem, investigations of the long-term variations of solar activity demand special methods and approaches.

4.1. METHOD OF DECOMPOSITION IN TERMS OF PSEUDO-PHASE SPACE (DPS-METHOD)

Takens (1981) has established a *topological* equivalence of the phase space (the space of variables describing a dynamic system) and the pseudo-phase space, formed by an observable variable $x(t)$:

$$\{x(t), x(t+\Delta), \ldots, x(t+n\Delta)\}\,.$$

If we search for links between $y(t)$ and $x(t)$ and assume that these links are described by a system of differential equations, for reconstruction of $y(t)$ it is possible to use a decomposition $x(t)$ in terms of the delay-time space:

$$y(t) = a_0 x(t) + a_1 x(t+\Delta) + \cdots + a_n x(t+n\Delta),$$

where Δ and n are searched for by rules of *nonlinear dynamics*.

Let us note that from the formal point of view the method is similar to autoregression methods, but it directly establishes values of shift Δ and the necessary number of terms n in the last formula.

In Figure 4 an example of applying the procedure, the DPS-reconstruction of the 5 pt-smoothed yearly N–S asymmetry time set using GSN series is shown. The correlation coefficient between the reconstructed set and observational data (from ESAI, 1826–1989, and Ribes and Nesme-Ribes (1993), 1670–1720) is 0.95.

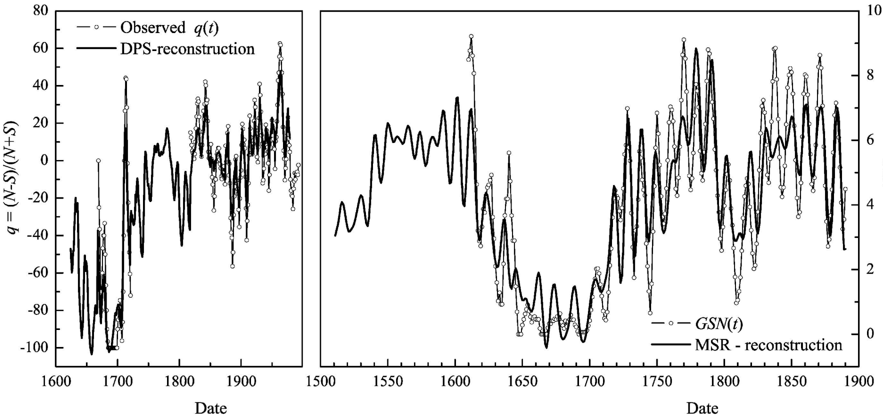

Figure 4. DPS-reconstruction of yearly N–S asymmetry series (*left panel*) and MSR-reconstruction of yearly Group Sunspot Numbers based on radiocarbon series by Stuiver, Reimer, and Braziunas (*right panel*).

4.2. MULTI-SCALE REGRESSION METHOD (MSR-METHOD)

The MSR-method (Nagovitsyn *et al.*, 2003) allows uncovering and accounting for possible links between time series that have different correlation for different time scales. It is based on construction of multi-dimensional regression models in the space of wavelet-coefficients, which is followed by a subsequent inverse wavelet transform. In short, the idea of the method is as follows.

The wavelet transform of the original series $f(t)$,

$$[Wf](a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\psi^* \left(\frac{t-b}{a} \right) dt,$$

produces its decomposition with a basis formed by orthogonal dilations and translations of a base wavelet – a function, localized both in frequency and time. A set of values $a = 2^q, q = 1, 2, \ldots, p$ allows "splitting" of $f(t)$ into p components that present various scales and cover the whole frequency range. Let us suppose that we want to investigate the relation of a function $Y(t)$ with some set of functions $X_i(t),\ i = 1, 2, \ldots, m$. In accordance with the idea of the MSR-method, we make the wavelet transformation of all these functions and regard for each of the scales (the components of wavelet transform) the MLS-approximation of possible functional relations in the form of regression model:

$$\begin{aligned}[WY](2^q, t) = c_0^q + c_1^q\, [WX_1](2^q, t) + \\ + c_2^q\, [WX_2](2^q, t) + \cdots + c_m^q\, [WX_m](2^q, t).\end{aligned}$$

Having found the MLS-approximation $\overline{[WY]}(2^q, t),\ q = 1, 2, \ldots, p$, we can make the inverse wavelet transform, thereby obtaining a representation of $Y(t)$ behaviour by means of "factors" $X_i(t)$, which make, generally speaking, different contributions to the regression for different scales. The correlation coefficient between the obtained series $\bar{Y}(t)$ and the original one $Y(t)$ will indicate success of the approximation (or its failure).

As an example, the MSR-reconstruction of 5 pt-smoothed yearly Group Sunspot Numbers based on the radiocarbon series by Stuiver, Reimer, and Braziunas (1998) is shown in Figure 4. The associated correlation coefficient in term of $\mathrm{GSN}^{1/2}$ is 0.90. Among other things in Figure 4 one can see that the 11-year cycle does not disappear during Maunder minimum.

5. Millennial Time Scale: SA Proxies and Confidence in Them

At present for investigations of solar activity in the past we dispose of the following proxies ("witnesses of the history of the Sun"): historical naked-eye sunspot observations, historical auroral observations, concentration of cosmogenic isotope ^{14}C in tree rings, concentration of cosmogenic isotope ^{10}Be in polar ices and others (among other things, e.g. simulated data by Nagovitsyn, 1997b, or archeo-magnetic data by Volobuev, 2004, etc.).

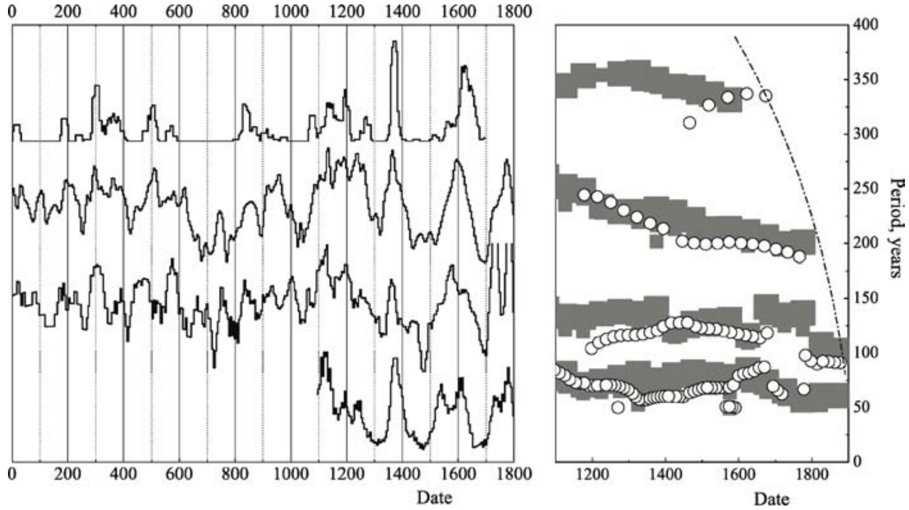

Figure 5. Left panel: solar activity proxies over millennial time scale. From top to bottom, naked eye sunspot series (Nagovitsyn, 2001), detrended radiocarbon series (Stuiver, Reimer, and Braziunas, 1998), detrended aurora series (Křivský, 1984), and the nonlinear model's Wolf number series (Nagovitsyn, 1997b), respectively. *Right panel:* variations of periods of long cycles of solar activity (*grey areas*) and global terrestrial temperature (*white circles*).

The general way to describe magnetic activity of the Sun on the prolonged time scale is generalization of various indirect data. Let us note that while earlier investigators used for reconstruction of the solar activity the behaviour in the past of discrete sources of data (carbon-14, beryllium-10, aurorae, observed by naked eye sunspots, etc., taken separately), we believe that *only synthesis of these heterogeneous data can provide reliability of the reconstructions*. The left panel of Figure 5 can serve as an illustration of our optimism. In Figure 5, right panel, data on variations of periods of long cycles (from 70 to 350 years) are brought together (grey areas). These data are obtained by application of wavelet transform (Morlet's wavelet of sixth order was used) to the following time series: radiocarbon production, historical aurora, naked eye sunspots, and simulated $W(t)$. The white circles mark variations of the corresponding periods for such a climatic parameter as the global terrestrial temperature (Mann and Bradley, 2000). One can see quite good similarity between behaviour of the solar and temperature parameters. Therefore, this picture confirms our belief in conditionality of climatic changes by solar activity (at least on large time scales), that is of importance for the aims of the work intended in Introduction.

6. Conclusions

In this paper, we presented a new information resource (ESAI) to study long-term solar magnetic field variations and its influence on the Earth. We also described some features of solar activity that seem obvious from the data obtained by us and discussed some problems of investigations of “the history of the Sun.”

It must be emphasized that ESAI database is focused on researches of the solar activity understood as *a complex physical phenomenon* of non-stationary dynamics of the solar magnetic field. Therefore, the manifold of indexes of the activity were considered.

It is shown that the (varying) duration of 11-year cycle as a parameter of oscillatory process is a universal quantity for different indices of the global magnetic field of the Sun.

The behaviour of the solar cyclicity during the Maunder minimum, upon which we have slightly touched, requires further studies. In particular, it is interesting to clarify whether the revealed periodicity is a real increase of duration of the 11-year cycle, or the phenomenon is determined by increase of the 22-year cycle amplitude, like Usoskin and Mursula (2003) assume.

The result in Figure 5 obtained by use of the integration of different solar activity proxy seems promising for understanding of solar-terrestrial climate links. We believe that the consideration of concurrent proxy data as well as different prolonged observational sets is important for further studying of the long-term solar variability and climate change in the past.

Acknowledgements

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References

Carbonell, M., Oliver, R., and Ballester, J. L.: 1993, *Astron. Astrophys.* **274**, 497.
Grossman, A. and Morlet, J.: 1984, *SIAM J. Math.* **15**, 723.
Gnevysheva, R. S.: 1994, *Catalog of Solar Activity. 1949–1989*, Central Astronomical Observatory at Pulkovo, Leningrad, Russia.
De la Rue, W., Stewart, B., and Loevy, B.: 1870, *Phil. Trans.* **160**, 389.
Hathaway, D. H., Wilson, R. M., and Reichmann E. J.: 2002, *Solar Phys.* **211**, 357.
Křivský, L.: 1984, *Solar Phys.* **93**, 189.
Makarov, V. I. and Makarova, V. V.: 1996, *Solar Phys.* **163**, 267.
Mann, M. E., and Bradley, R. S.: 1999, *Geophys. Res. Lett.* **26**, 759.
Nagovitsyn, Yu. A.: 1988, *“Solnechnye dannye”. Bull.* 8, 88.
Nagovitsyn, Yu. A.: 1997a, *“Solnechnye dannye. 1995–1996” Bull.* 38.
Nagovitsyn, Yu. A.: 1997b, *Astron. Lett.* **23**, 742.
Nagovitsyn, Yu. A.: 2001, *Geomagn. Aeron.* **41**, 711.

Nagovitsyn, Yu. A., Ivanov, V. G., Miletsky, E. V., and Volobuev D. M.: 2003, in *Proceedings of the International Conference-Workshop on* “Cosmogenic climate forcing factors during the last millennium”, Kaunas, Lithuania, p. 41.

Ribes, J. C. and Nesme-Ribes: 1993, *Astron. Astrophys.* **276**, 549.

Sheeley, N. R., Jr: 1991, *Astrophys. J.* **374**, 386.

Solanki, S. K., Krivova, N. A., Schüssler, M., and Fligge, M.: 2002, *Astron. Astrophys.* **396**, 1029.

Stuiver, M., Reimer, P. J., and Braziunas, T. F.: 1998, *Radiocarbon* **40**, 1127.

Takens, F.: 1981, *Lect. Notes Math.* **898**, 366.

Usoskin, I. G. and Mursula, K.: 2003, *Solar Phys.* **218**, 319.

Usoskin, I. G., Mursula, K., and Kovaltsov, G. A.: 2001, *Geophys. Res. Lett.* **106**, 16039.

Vaquero, J. M., Gallego, M. C., and Sanchez-Bajo, F.: 2004, *Solar Phys.* **221**, 179.

Volobuev, D. M.: 2004, *Solar Phys.*, this issue, 387.

Waldmeier, M.: 1935, *Astron. Mitt. Zürich* **14**, 105.

Wittman, A. D. and Xu, Z. T.: 1987, *Astron. Astrophys. Suppl. Ser.* **70**, 83.