Deep minima of the Sun’s activity according to data of solar paleoastrophysics

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Abstract. Twenty paleoreconstructions of the Sun’s activity, obtained using the data on both cosmogenic isotopes and auroral records, are generalized over a time interval 1402-1850. Final reconstruction of sunspot number is obtained by means of normalization of the generalized record by the instrumentally measured series \( S_N \). Comparison of average levels of solar activity during the periods of solar minima of Spoerer (1415-1545), Maunder (1645-1715) and Dalton (1792-1827) is made. Discussion of the results is presented.

1. Introduction
Prolonged and deep minima of solar activity attract interest of scientists during the last decades [1-4]. Dalton minimum (DM, AD 1792-1827) is the most studied episode of low solar activity (SA). Maunder minimum (MM, AD 1645-1715) and Spoerer minimum (SM, 15-16th centuries) likely were both longer and deeper than the DM. However, our knowledge of SA during these two epochs is rather limited. Interesting hypotheses on SA changes over these two periods have appeared recently. Zolotova and Ponyavin [5] have concluded that the MM was an ordinary minimum of SA activity like the DM. The authors of the work [6] arrived at conclusion that the 15-16th centuries was a period of high SA. These findings have been criticized [7, 8]. Considering the above controversy Ogurtsov [9] started profound research of SA during the last centuries using all the information collected by solar paleoastrophysics. The present work follows the approach developed in [9] i.e. is devoted to analysis of proxy SA records spanning last 6 centuries.

2. Data
Taking into account that some authors noted that the 15th and 16th centuries were a period of relatively high auroral activity [10,11] I added to a number of solar paleoindicators the four ones, which include auroral information:

1) The auroral catalogue of Krivsky and Pejml [12] spanning time interval AD 1000-1900 and including auroae observations made at high (>55°) latitudes. This record has a strong increasing trend. This trend is caused by the so-called “civilization factors”: increasing number of chroniclers and their reports, increased interest in natural phenomena, letter-print factor etc. [13]. Process of the dispersion of information with time can also play a role [14]. According to [14] the trend has exponential shape. Thus I corrected the auroral record for “civilization factors” by the exponent with a half-decay time of 120 years.
2) The auroral record of Křivsky (1984) spanning time interval AD 1000-1848 and including 40 years sums of aurorae observations made at high (>55°) latitudes. This series was homogenized, i.e. corrected for civilization factors by the author.

3) The time series of dates and maxima of 11-year solar cycles reconstructed by Schove [1]. This data set cover time interval after 648 BC. Schove used mainly the ancient auroral observations in his reconstruction. The data of the work [1] can be considered a bit obsolete. On the other hand, forecast of maxima of the solar cycles made by Schove [1] looks convincing: 100 at 1972.5, 150 at 1984.5, 110 at 1994.5, 100 at 2004.5, 90 at 2014.5.

4) The reconstruction of the sunspot number made in the work [15] by means of the data on the radiocarbon concentration in tree rings, auroral observations and sunspots observed by naked eye. This series spans the time interval 30–2000 and has a time resolution of 5 years. It

3. Results

The present research was made by the method similar to that, which was used by Ogurtsov [9]. The main difference is that the new sunspot series $S_N$ [16] was used for the SA reconstruction instead of the Group Sunspot Number $R_G$ used in the work [9]. This version of the sunspot number was accepted in 2015. It includes some significant changes and thus is considered as essentially improved (see [17]). All the SA reconstructions have been preliminary smoothed by 11 years. Generalization of the 20 time series was made by: (a) calculating their Z score (the average time series, normalized to zero mean and unit variance), (b) calculating the first principal component of these 20 data sets. This first component explains 70% of the total variance. After that, in the interval 1700–1850, I constructed linear regressions between the generalized sunspot records and the $S_N$ smoothed over 13 years. By means the calculated regressions, sunspot number was reconstructed over the entire interval 1402–1850. The two generalized sunspot series are presented in Figure 1. I’ll call them as reconstructed sunspot number $R_{SN}$.

![Figure 1](image-url)

**Figure 1.** The sunspot number determined by generalizing of the 20 solar proxies. The thick black line indicates the $R_{SN}$ derived using the mean over the normalized reconstructions. The thin black line indicates the $R_{SN}$ derived using the first principal component (66% of the total variance). The thick grey line indicates the $S_N$ measured instrumentally and smoothed by 13 years.

Uncertainty of the reconstructed $R_{SN}$ series was estimated within interval 1402-1850 by means of the residual variance – the sum of variances of the other components (34% of the total variance). It is 13-14. The results of the reconstruction are shown in Table 1 also.
Perform analysis has shown that the solar minima of Maunder and Sporer really were the periods of very quiet Sun with an average level of SA appreciably lower than during the Dalton minimum (see Figure 1, Table 1). On the other hand the mean value of $R_{SN}$ over the MM (1645-1715) appreciably differs from zero. The value 29.5-33.4 corresponds to a mean annual value of $S_N$ in 1987 and 1997 i.e. the mean value of the observed sunspot groups during the MM $\overline{G}_{MM} = 1.6-1.9$ (see [18]). This doesn’t match well with results of some other works indicating appreciably lower SA during the MM. E.g. Hoyt and Schatten [19], who generalized a lot of European telescopic data, considered the MM as a period which is characterized by a nearly complete absence of sunspots. According to the work [19] $\overline{G}_{MM} = 0.05$. Ogurtsov [9], who normalized the paleoastrophysical data on the group sunspot number $R_G$, has obtained at the MM a weak activity ($\overline{R}_G = 7-8$) corresponding to $\overline{G}_{MM} = 0.7-0.9$.

According to the record of Svalgaard and Schatten [20], based on astronomical data, $\overline{G}_{MM} = 1.0$. Vaquero et al [7], who also used astronomical information, arrived at conclusion that during the MM the maximum yearly mean value of $R_G$ was less than 10. On the other hand some other results give evidences for stronger SA during the MM. E.g. Nagovitsyn and Ogurtsov [21], who analyzed the data on concentration of $^{14}$C, $^{10}$Be and nitrates in terrestrial archives, arrived at conclusion that during the MM maximum annual $R_G$ value reached 25 (and even 40 at the beginning). In the work [22] this result was regarded as overestimated. But then Zolotova and Ponyavin [5], who used telescopic data, concluded that during the MM the maximum yearly mean sunspot number reached 35 (80 at the beginning). Despite these values look overestimated too, it is evident that some controversy about the actual level of SA within the MM still is retained. Thus further efforts are need to reach the robust conclusion about behavior of the Sun during grand minima.

### Table 1. Reconstructed sunspot number during 1415-1850.

| Time series | The mean value of $R_{SN}$ during the specific period |
|-------------|------------------------------------------------------|
| 1415-1485  | 16.8±3.3                                            |
| 1486-1545  | 31.0±4.4                                            |
| 1546-1645  | 64.2±3.5                                            |
| 1646-1715  | 29.5±3.8                                            |
| 1715-1792  | 88.5±8.7                                            |
| 1793-1827  | 52.4±5.5                                            |
| 1828-1850  | 78.5±5.7                                            |

4. Discussion and conclusion

Performed analysis has shown that the solar minima of Maunder and Sporer really were the periods of very quiet Sun with an average level of SA appreciably lower than during the Dalton minimum (see Figure 1, Table 1). On the other hand the mean value of $R_{SN}$ over the MM (1645-1715) appreciably differs from zero. The value 29.5-33.4 corresponds to a mean annual value of $S_N$ in 1987 and 1997 i.e. the mean value of the observed sunspot groups during the MM $\overline{G}_{MM} = 1.6-1.9$ (see [18]). This doesn’t match well with results of some other works indicating appreciably lower SA during the MM. E.g. Hoyt and Schatten [19], who generalized a lot of European telescopic data, considered the MM as a period which is characterized by a nearly complete absence of sunspots. According to the work [19] $\overline{G}_{MM} = 0.05$. Ogurtsov [9], who normalized the paleoastrophysical data on the group sunspot number $R_G$, has obtained at the MM a weak activity ($\overline{R}_G = 7-8$) corresponding to $\overline{G}_{MM} = 0.7-0.9$.

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