Millennium-Scale Sunspot Number Reconstruction:
Evidence for an Unusually Active Sun since the 1940s

Ilya G. Usoskin*

Sodankylä Geophysical Observatory (Oulu unit), University of Oulu, FIN-90014 Oulu, Finland

Sami K. Solanki[†] and Manfred Schüssler

Max-Planck Institut für Aeronomie, Katlenburg-Lindau, Germany

Kalevi Mursula and Katja Alanko

Department of Physical Sciences, University of Oulu, FIN-90014 Oulu, Finland
(Received 9 July 2003; published 19 November 2003)

The extension of the sunspot number series backward in time is of considerable interest for dynamo theory, solar, stellar, and climate research. We have used records of the ^{10}Be concentration in polar ice to reconstruct the average sunspot activity level for the period between the year 850 to the present. Our method uses physical models for processes connecting the ^{10}Be concentration with the sunspot number. The reconstruction shows reliably that the period of high solar activity during the last 60 years is unique throughout the past 1150 years. This nearly triples the time interval for which such a statement could be made previously.

PACS numbers: 96.60.Qc, 96.40.Kk

The sunspot number (SN) series represents the longest running direct record of solar activity, with reliable observations starting in 1610, soon after the invention of the telescope. The behavior of solar activity in the past, before the era of direct measurements, is of importance for a variety of reasons. For example, it allows an improved knowledge of the statistical behavior of the solar dynamo process which generates the cyclically varying solar magnetic field. It also should help to produce superior estimates of the fraction of time the Sun spends in states of very low activity, the so-called great minima, such as the Maunder minimum in the second half of the 17th century. This is of particular interest when comparing the behavior of the Sun with that of other Sun-like stars [1]. The level of solar activity also affects the Sun's radiative output [2], which in turn may influence the Earth's climate [3]. However, any such influence takes place on time scales longer than the solar cycle, so that a statistically significant comparison with paleoclimatic records requires a long time series of solar activity data.

We are specifically interested in the past evolution of sunspot activity. Sunspots lie at the heart of solar active regions and trace the emergence of large-scale magnetic flux, which is responsible for the various phenomena of solar activity. Consequently, sunspots are a good tracer for solar magnetic activity, particularly so during times of medium to high activity.

The sunspot number record shows intriguing contrasts between the extremes reached during the Maunder minimum when practically no sunspots were seen on the face of the Sun [4,5], and in the period since the 1940s when SN reached the average value of about 75. Extensions to earlier times have been attempted in the past by extrapolating this record, based on mathematical modeling using statistical properties of the observed SN record [6,7] or adjusting them to fragmentary data on naked-eye sunspot and auroral observations [8]. Such extrapolations suffer from rapidly increasing uncertainty for earlier times. Alternatively, the SN prior to 1610 has been estimated from archival proxies, such as the concentration of cosmogenic ^{14}C isotope in tree rings or ^{10}Be isotope in ice cores drilled in Greenland and Antarctica [9–11]. For want of a physical relationship, a simple linear regression between the SN and the isotope concentration has generally been assumed.

Recently, detailed physical models have been developed for each individual link in the chain connecting the SN with the cosmogenic isotopes. This includes a physical model relating the heliospheric magnetic flux (the Sun's open magnetic flux) to the SN [12,13], a model for the transport and modulation of galactic cosmic rays within the heliosphere [14], and a model describing the ^{10}Be isotope production in the terrestrial atmosphere [15,16]. We have combined these models, such that the output of one model becomes the input for the next step. It has thus become possible to model the complete sequence of processes and to calculate the expected ^{10}Be concentration from 1610 onwards on the basis of the SN record [17,18]. The inversion of this chain has been successfully demonstrated as well [18]. For artificial, noise-free ^{10}Be data the yearly SN could be reconstructed with an error of ± 10 compared with the typical solar maximum SN of over 100 during recent cycles. For real ^{10}Be data, the noise makes the reconstruction of yearly sunspot numbers impractical, but robust reconstructions of 11-year (solar cycle) averages of this quantity are shown to be possible.

Following the recent approach [18] we present here a reconstruction of the SN since the year 850, based upon the measured ^{10}Be concentrations in ice cores at the Dye-3 site in Greenland (annual data for 1424–1985) [9] and at the South Pole (roughly 8-year sampled data for 850–1900) [19].

Sunspot number reconstruction.—The reconstruction comprises five steps, which are described in detail by Usoskin *et al.* [17,18]:

$$^{10}\text{Be} \xrightarrow{(1)} \text{CR} \xrightarrow{(2)} \Phi \xrightarrow{(3)} F_o \xrightarrow{(4)} S \xrightarrow{(5)} \text{SN}. \qquad (1)$$

First the flux of cosmic rays (CR) impinging on the Earth's atmosphere is derived from the measured ^{10}Be concentration. This yields the modulation strength Φ of cosmic rays through a model of heliospheric transport of cosmic rays [14], which in turn is used to determine the Sun's open magnetic flux F_o. The model [12,13] of Solanki *et al.* is employed to obtain the source term S for the open magnetic flux and, finally, the sunspot number SN. We use a realistic ^{10}Be yield function [15] and include also heavier species of cosmic rays, in particular, α particles, whose contribution to the ^{10}Be production is about 30%. The advantage of our physical reconstruction is that it takes into account the nonlinear nature of the relation between ^{10}Be concentration and SN and thus returns more reliable values of SN once the parameters of the physical models are fixed on the basis of actual measurements. For the period of time from 1700 to 1940 when both SN and ^{10}Be data sets are reliable, Fig. 1 illustrates the improvement achieved with our reconstruction method (left panel) compared to a linear regression between the SN and the ^{10}Be production rate (right panel). The distinct excursions over limited time intervals (open circles: 1722–1743, 1761–1789, 1828–1845, 1882–1894)
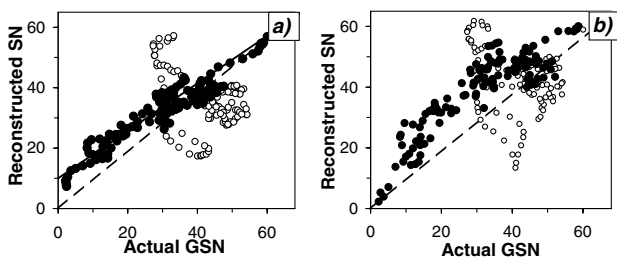

FIG. 1. Scatter plots of annual sunspot numbers (SN) reconstructed from the 11-year smoothed Greenland Dye-3 ^{10}Be data [9] vs the annual, 11-year smoothed group sunspot number for the period 1700–1940 [26]. Left: results from our physical reconstruction method. We find a nearly linear relation (solid dots) with a small amount of scatter, except for four excursions (open dots) during specific periods of time. These stronger deviations are probably caused by climatic effects. Right: results of a fit based upon linear regression between group sunspot number and ^{10}Be production rate. Our physical model yields a much closer relation between the actual and the reconstructed SN than the purely statistical approach.

are probably due to local climatic effects in Greenland, as indicated by comparison with the ^{14}C data (see Fig. 2), which are much less affected by local climatic variability. Most of the time, however, the reconstructed SN is closely related to the actual SN observations [22], with the full dots showing a considerably smaller scatter (with a linear correlation coefficient of $r = 0.96$) than the corresponding result using a linear regression ($r = 0.81$). While our reconstruction reproduces the SN at intermediate to high levels of solar activity relatively well, it tends to overestimate the SN during periods of low activity. This partly reflects the existence of a residual level of magnetic activity which modulates the cosmic ray flux even in times of almost vanishing sunspots [23,24]. Such activity could, e.g., be due to the emergence of small, spotless ephemeral active regions [13,25]. The SN based on our physical reconstruction can therefore be considered as upper limits during periods of low SN. The assumption that ^{10}Be is deposited locally [18] may also contribute to the offset at small SN seen in Fig. 1. Mixing in the terrestrial atmosphere would cause the ^{10}Be concentration to be affected by geomagnetic variations. Since the Earth's magnetic field was stronger during the Maunder minimum than it is today, neglecting this change could lead to an overestimate of the reconstructed SN. We have used the (nearly linear) relationship between the actual and the reconstructed values on the left panel of Fig. 1 to apply a simple correction to the reconstruction, which mainly affects the low SN values.

Figure 2 shows the SN reconstructed from the (1-2-1 averaged) 8-year sampled Antarctic ^{10}Be record for the years 850–1900 [19] and from the (11-year smoothed) Greenland Dye-3 record for the period 1424–1985 [9]. Also given is the similarly averaged group sunspot number [26] based on observations after 1610 and the (scaled) ^{14}C concentration in tree rings, corrected for the change of the geomagnetic field [20,21]. For easier comparison, the latter curve has been scaled to match the mean and the range of the reconstructed SN. The reconstructed SN profiles depicted by the (red and green) colored areas are bounded from above by the actual reconstruction results and from below by the low SN corrected results described above.

The reconstructed SN series confirms the various great minima and also the medieval maximum (roughly between the years 1100 and 1250) identified in previous, statistical studies of the ^{10}Be and ^{14}C records [19,21]. The two reconstructed and the measured SN series generally are in good agreement after the end of the Maunder minimum around 1700. The differences between the results from the Antarctica and the Greenland ^{10}Be records are greater in 1450–1700, during the so-called "little ice age" [4], and they can possibly be ascribed to local climatic effects in ^{10}Be deposition. This interpretation is supported by the good correlation between the reconstruction from the Antarctica data and the ^{14}C record
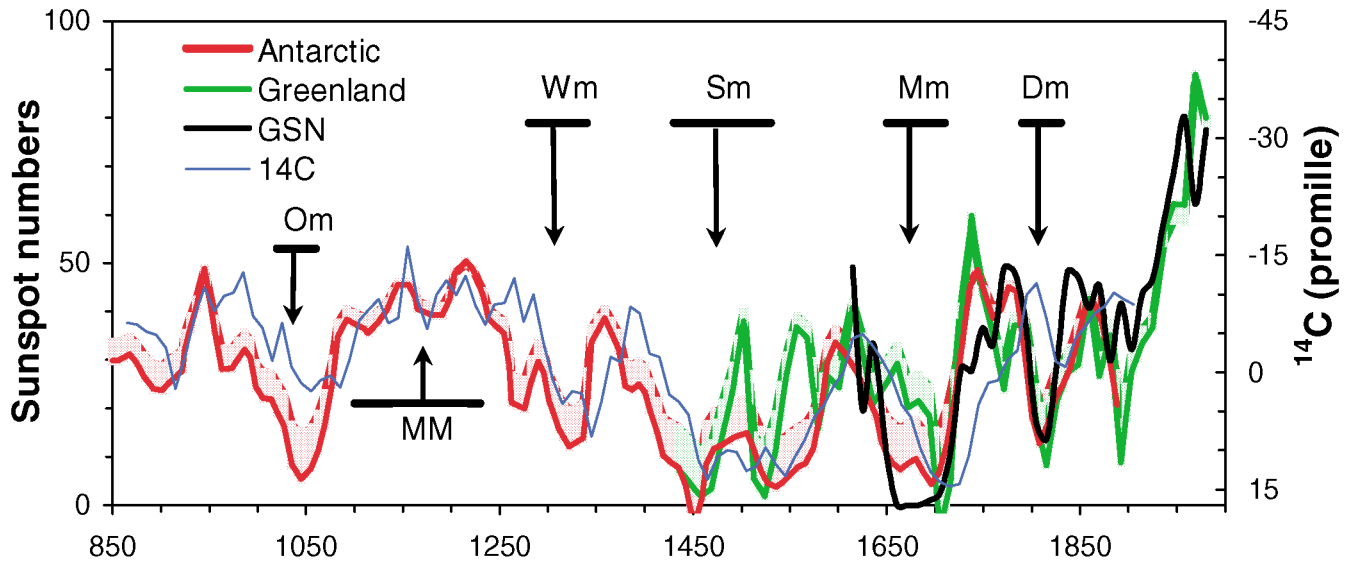
FIG. 2 (color). Time series of the sunspot number as reconstructed from ^{10}Be concentrations in ice cores from Antarctica (red) and Greenland (green). The corresponding profiles are bounded by the actual reconstruction results (upper envelope to shaded areas) and by the reconstructed values corrected at low values of the SN (solid curves) by taking into account the residual level of solar activity in the limit of vanishing SN (see Fig. 1). The thick black curve shows the observed group sunspot number since 1610 and the thin blue curve gives the (scaled) ^{14}C concentration in tree rings, corrected for the variation of the geomagnetic field [20]. The horizontal bars with attached arrows indicate the times of great minima and maxima [21]: Dalton minimum (Dm), Maunder minimum (Mm), Spörer minimum (Sm), Wolf minimum (Wm), Oort minimum (Om), and medieval maximum (MM). The temporal lag of ^{14}C with respect to the sunspot number is due to the long attenuation time for ^{14}C [19].

during this period, once the phase shift of about 20 years due to the long attenuation time for ^{14}C [19] has been taken into account.

The most striking feature of the complete SN profile is the uniqueness of the steep rise of sunspot activity during the first half of the 20th century. Never during the 11 centuries prior to that was the Sun nearly as active. While the average value of the reconstructed SN between 850 and 1900 is about 30, it reaches values of 60 since 1900 and 76 since 1944. For the observed group SN series since 1610 these values are 25, 61, and 75, respectively. The largest 100-year average of the reconstructed SN prior to 1900 is 44, which occurs in 1140–1240, i.e., during the medieval maximum, but even this is significantly less than the level reached in the last century. The medieval maximum is remarkable, however, in the length of time that the Sun has consistently remained at the average SN level of about 40–50. Only during the recent period of high activity since about 1830, i.e., after the Dalton minimum, has the SN remained consistently above 30 for a similar length of time. We conclude that the high level of solar activity since the 1940s is unique since the year 850. This can be considered a robust conclusion since we have shown that our reconstruction is particularly reliable in phases of high and intermediate sunspot activity, while during periods of low activity the SN may be overestimated.

The good overall agreement of the reconstructed SN with the ^{14}C data further supports the reliability of our reconstruction: the cross-correlation coefficient (taking into account the overall 20-year delay in ^{14}C concentration) is 0.83 ± 0.07. Since the globally mixed ^{14}C is not affected by the vagaries of the local climate, the good correspondence between the ^{14}C curve and the SN reconstructed from the Antarctic ^{10}Be data indicates that long-term climatic variability does not strongly affect our results. This conclusion is reinforced by the good agreement between the measured ^{14}C concentrations and the corresponding values derived from the ^{10}Be data on the basis of a ^{14}C redistribution model [19]. The fact that the reconstruction based on the Greenland Dye-3 core shows stronger deviations from ^{14}C during the little ice age suggests that the Greenland ^{10}Be record is more strongly affected by local climate fluctuations [19].

It is known that the geomagnetic field has decreased by about 30% during the last 1000 years (see, e.g., [27]). The stronger geomagnetic field in earlier times has led to a more effective shielding of cosmic rays and may, depending on the amount of atmospheric mixing of ^{10}Be before precipitation, have caused a reduced ^{10}Be production. Our calculations use the present geomagnetic field and neglect the possible effect of the changing geomagnetic field. This is probably well justified at least for the Antarctica record [18], as indicated by the good correspondence with the ^{14}C record, which has been corrected for changes of the geomagnetic field [20]. In any case, without such correction our reconstruction model ascribes any effect of a stronger geomagnetic field to a higher SN in the past.

Consequently, our reconstructed SN values in the pre-telescopic era are to be considered as upper bounds, emphasizing even more the exceptional nature of the high solar activity during the last 60 years.

Although our SN reconstruction still covers a rather limited length of time (but nonetheless about 3 times longer than the telescopic sunspot record), the unusually high number of sunspots during the past century suggests that we currently may be seeing a state of the solar dynamo that is uncharacteristic of the Sun at middle age. Also, the higher activity level implies more coronal mass ejections and more solar energetic particles hitting the Earth. Thus we expect that the late 20th century has been particularly rich in phenomena like geomagnetic storms and aurorae. The flux of energetic galactic cosmic rays (in the neutron monitor energy range above several GeV) reaching the Earth is presently about 10% lower than it was around 1900 [17]. The suppression of lower-energy cosmic rays (about 2 GeV), which are mainly responsible for the production of cosmogenic isotopes, is even stronger, reaching up to 40%.

The current high level of solar activity may also have an impact on the terrestrial climate. We note a general similarity between our long-term SN reconstruction and different reconstructions of temperature [28,29]: (1) both SN and temperature show a slow decreasing trend just prior to 1900, followed by a steep rise that is unprecedented during the last millenium; (2) great minima in the SN data are accompanied by cool periods while the generally higher levels of solar activity between about 1100 and 1300 correspond to a relatively higher temperature (the medieval warm period) [30]. To clarify whether this similarity reflects a real physical connection requires a more detailed study of the various proposed mechanisms for a solar influence on climate [31].

----

*Electronic address: Ilya.Usoskin@oulu.fi
†Electronic address: Solanki@linmpi.mpg.de

[1] S. Baliunas and R. Jastrow, Nature (London) **348**, 520 (1990).
[2] R. C. Willson and H. S. Hudson, Nature (London) **351**, 42 (1991).
[3] S. K. Solanki and M. Fligge, Geophys. Res. Lett. **25**, 341 (1998).
[4] J. A. Eddy, Science **192**, 1189 (1976).
[5] J. C. Ribes and E. Nesme-Ribes, Astron. Astrophys. **276**, 549 (1993).
[6] Yu. A. Nagovitsyn, Astron. Lett. **23**, 742 (1997).
[7] N. R. Rigozo, E. Echer, L. E. A. Vieira, and D. J. R. Nordemann, Sol. Phys. **203**, 179 (2001).
[8] D. J. Schove, J. Geophys. Res. **60**, 127 (1955).
[9] J. Beer et al., Nature (London) **347**, 164 (1990).
[10] P. E. Damon and C. P. Sonett, in *The Sun in Time*, edited by C. P. Sonett, M. S. Giampapa, and M. S. Matthews (University of Arizona Press, Tucson, 1991), p. 360.
[11] J. Beer, Space Sci. Rev. **94**, 53 (2000).
[12] S. K. Solanki, M. Schüssler, and M. Fligge, Nature (London) **408**, 445 (2000).
[13] S. K. Solanki, M. Schüssler, and M. Fligge, Astron. Astrophys. **383**, 706 (2002).
[14] I. G. Usoskin, K. Alanko, K. Mursula, and G. A. Kovaltsov, Sol. Phys. **207**, 389 (2002).
[15] W. R. Webber and P. R. Higbie, J. Geophys. Res. **108(A9)**, 1355 (2003).
[16] J. Masarik and J. Beer, J. Geophys. Res. **104(D10)**, 12099 (1999).
[17] I. G. Usoskin, K. Mursula, S. K. Solanki, M. Schüssler, and G. A. Kovaltsov, J. Geophys. Res. **107(A11)**, 1374 (2002).
[18] I. G. Usoskin, K. Mursula, S. K. Solanki, M. Schüssler, and K. Alanko, astro-ph/0309556 [Astron. Astrophys. (to be published)].
[19] E. Bard, G. M. Raisbeck, F. Yiou, and J. Jouzel, Earth Planet. Sci. Lett. **150**, 453 (1997).
[20] M. Stuiver and P. Quay, Science **207**, 11 (1980).
[21] M. Stuiver and T. F. Braziunas, Nature (London) **338**, 405 (1989).
[22] During the period 1722–1743, the reconstructed SN is closer to the Wolf SN series than to the group SN.
[23] J. Beer, S. Tobias, and N. O. Weiss, Sol. Phys. **181**, 237 (1998).
[24] I. G. Usoskin, K. Mursula, and G. A. Kovaltsov, J. Geophys. Res. **106(A8)**, 16039 (2001).
[25] K. L. Harvey, in *The Solar Cycle*, edited by K. L. Harvey, ASP Conf. Series Vol. 27 (Astronomical Society of the Pacific, San Francisco, 1992), p. 235.
[26] D. V. Hoyt and K. Schatten, Sol. Phys. **179**, 189 (1998).
[27] S. Baumgartner, J. Beer, and H. A. Synal, Science **279**, 1330 (1998).
[28] M. E. Mann, R. S. Bradley, and M. K. Hughes, Geophys. Res. Lett. **26**, 759 (1999).
[29] P. D. Jones, T. J. Osborn, and K. R. Briffa, Science **292**, 662 (2001).
[30] R. S. Bradley et al., Science **292**, 2011 (2001).
[31] *Solar Variability and Climate*, edited by E. Friis-Christensen, C. Fröhlich, J. D. Haigh, M. Schüssler, and R. von Steiger, Space Science Reviews Vol. 94 (Kluwer, Dordrecht, 2000).