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Solar activity reconstructed over the last 7000 years: The influence of geomagnetic field changes

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[1] The long-term solar activity, as manifested by sunspot number, has been recently reconstructed on multi-millennium time scales by S. K. Solanki et al. (2004) from the measured concentration of ^{14}C in tree rings. The exact level of the reconstructed solar activity depends, however, on independently evaluated data of the geomagnetic dipole strength variations. Recently, a new series of the palaeomagnetic dipole moment reconstruction for the last 7000 years has been presented by M. Korte and C. G. Constable (2005a) on the basis of a thorough analysis of global samples. The new palaeomagnetic series yields a systematically lower dipole moment in the past, compared to the earlier geomagnetic reconstructions. We have revised the earlier sunspot activity reconstruction since 5000 BC, using the new geomagnetic data series, and found that it is roughly consistent with the previous results during most of the period, although the revised sunspot number values are in general higher. Nonetheless, it is confirmed with the new palaeomagnetic series that the Sun spends only 2–3% of the time in a state of high activity, similar to the modern episode. This strengthens the conclusion that the modern high activity level is very unusual during the last 7000 years. **Citation:** Usoskin, I. G., S. K. Solanki, and M. Korte (2006), Solar activity reconstructed over the last 7000 years: The influence of geomagnetic field changes, *Geophys. Res. Lett.*, *33*, L08103, doi:10.1029/2006GL025921.

1. Introduction

[2] The long-term behaviour of solar activity can be reconstructed from the measured cosmogenic isotope content in terrestrial archives [e.g., *Stuiver*, 1961]. Cosmogenic isotopes are produced in the Earth's atmosphere by energetic cosmic rays (CR) whose flux is modulated in the heliosphere by the turbulent heliospheric magnetic field and variable solar wind, both being ultimately defined by solar magnetic activity. The flux of CR impinging on the atmosphere is modulated not only by the heliosphere but also by the geomagnetic field. Therefore, any notable change in the geomagnetic field should be taken into account in such models as it can affect the solar activity levels reconstructed from cosmogenic isotopes. The most important is the dipole moment of the geomagnetic field, since higher order momenta drop rapidly from the Earth's surface and do not deflect CR effectively. Many earlier corrections for possible geomagnetic field changes were performed by detrending the measured ^{14}C abundance [*Damon et al.*, 1989; *Stuiver and Quay*, 1980; *Peristykh and Damon*, 2003], under the assumption that solar activity changes on time scales shorter than the geomagnetic field. Such a method, however, obliterates all information on possible long-term variations of solar activity. Later, simplified empirical correction factors were used [e.g., *Stuiver*, 1980; *Stuiver et al.*, 1991]. Recently developed appropriate physics-based models [*Beer et al.*, 2003; *Usoskin et al.*, 2003; *Solanki et al.*, 2004] allow full quantitative reconstruction of solar activity, explicitly using independent reconstructions of the geomagnetic field. Uncertainties of the geomagnetic data form an important source of errors in the solar activity reconstructions [see *Solanki et al.*, 2004, supplementary materials].

[3] Recently, *Solanki et al.* [2004] presented a reconstruction of sunspot numbers from the measured concentration of Δ^{14}C in tree rings by means of a physics-based model. The effect of the geomagnetic field was considered by making use of the geomagnetic virtual dipole moment data provided by *Yang et al.* [2000] before 850 AD, and a more detailed reconstruction [*Hongre et al.*, 1998; *Bloxham and Jackson*, 1992] after that. The 12,000-year long geomagnetic compilation by *Yang et al.* [2000] was also used in other studies [*Beer et al.*, 2003]. Another approach to the past geomagnetic moment reconstruction has been recently taken by Korte and Constable, who carried out a multipole expansion of the geomagnetic field based on fits to the measured data sets and reconstructed the geomagnetic dipole moment for the last 7000 years [*Korte and Constable*, 2005a]. Their reconstruction is systematically different from the virtual dipole moment published by *Yang et al.* [2000]. Since this new geomagnetic series can alter the previous reconstruction of long-term solar activity, we redo the whole reconstruction using the new geomagnetic series. We present these new results and also discuss the related uncertainties for the last 7000 years (after 5000 BC) covered by the new geomagnetic series. We also carry out and discuss further tests of the consistency of our sunspot reconstruction.

2. Geomagnetic Dipole Moment

[4] Although 90% of the geomagnetic field observed at the Earth's surface can be described by a tilted dipole, magnetic measurements including palaeo-/archaeomagnetic data can be significantly influenced by non-dipole field contributions. These have to be properly taken into account for an accurate reconstruction of the dipole moment (DM). The non-dipole field influence on local measurements of geomagnetic field intensity and directions cannot be directly determined and a world-wide distribution of measurements

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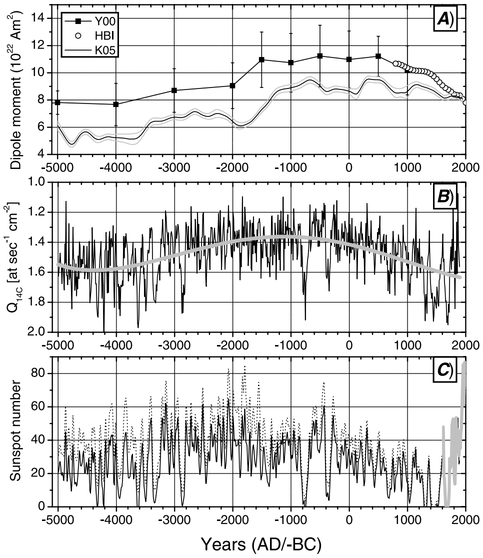

Figure 1. (a) Geomagnetic field intensity: VADM compilation by *Yang et al.* [2000] (Y00 curve with 1σ statistical errors of the sample distribution); DM computed using Gaussian spherical harmonics coefficients given by *Hongre et al.* [1998] before 1700, by *Bloxham and Jackson* [1992] in 1700–1900, and by the IGRF model after 1900 (HBI, open circles); DM given by *Korte and Constable* [2005a] (K05, solid curve) together with 1σ error band (grey shading). (b) ^{14}C global production rate [*Usoskin and Kromer*, 2005] together with the long-term trend represented by the best-fit 4th order polynomial. Note the inverted vertical scale. (c) Sunspot activity reconstructed by *Solanki et al.* [2004] (solid curve) and reconstructed using the same method but with the geomagnetic data by *Korte and Constable* [2005a] (dotted curve). The grey curve depicts the directly observed Group sunspot numbers [*Hoyt and Schatten*, 1998].

is necessary to obtain reliable DM estimates. If the magnetic inclination can be evaluated at each location, an approximation of the DM, called the virtual dipole moment (VDM), can be reconstructed. The VDM approximation assumes that the dipole is geocentrical and assigns the measured palaeointensity to the DM, further assuming that higher order terms are averaged out over different locations, which is not always true, especially for a non-even distribution of sampling sites. Furthermore, if the inclination cannot be reconstructed from original data (e.g., in the case of archaeomagnetic data), the dipole field is assumed to be aligned with the geographic axis. In this case the geomagnetic latitude is considered equal to the geographical latitude, and the corresponding VDM reconstruction is called the virtual axial dipole moment (VADM). Both VDM and VADM form a proxy for the true DM, but they include also non-dipole contributions assigned to the dipole strength. In addition, the VADM values can be further distorted by any tilt of the dipole axis. VADM and VDM estimates may differ significantly from the true DM, especially if not averaged over long time scales (see, for example, discussions by *Chauvin et al.* [2000], *McMillan et al.* [2004], and *Korte and Constable* [2005a].

[5] Different reconstructions of the geomagnetic dipole moment are shown in Figure 1a for the last 7,000 years. The "rough" Y00 curve with 500–1000 years time resolution presents the archeomagnetic VADM reconstruction by *Yang et al.* [2000]. A significant fraction of data points (2203 individual measurements) is related to European sites but the rest of the world is also covered (1040 measurements). However, the distribution of sampling sites was still not global, being mainly located on the northern hemisphere. Note that the data coverage was relatively good after 6000 BC, thus covering the period under investigation here, but drops dramatically before that. Error bars correspond to the standard deviation of distribution from individual data series and are quite large.

[6] The open circles denoted HBI represent DM computations using spherical harmonic coefficients as given by *Hongre et al.* [1998] before 1700 AD, by *Bloxham and Jackson* [1992] for the period 1700–1900 AD, and by the IGRF (International Geomagnetic Reference Field) model after 1900 AD. We will refer to a composite of Y00- before 850 AD and the HBI-series afterward, as M_{S04}, throughout the paper. As error bars for this series, we adopted those of the Y00-series since they correspond to the upper bound for statistical uncertainties of the geomagnetic reconstruction. The K05 curve in Figure 1a depicts the recent reconstruction of DM by *Korte and Constable* [2005a] using the CALS7K.2 model [*Korte and Constable*, 2005b]. We will refer to this series as M_{K05} throughout the paper. Note that, while the large error bars of the Y00-series reflect the standard deviation of the individual data sets contributing to the Y00 composite, the smaller errors of the K05-series depict the mean error of the reconstructed mean DM.

[7] The dipole moment reconstructed by *Korte and Constable* [2005a] is systematically lower than other reconstructions, which can be related to the different definitions (DM vs. VDM or VADM). The difference $\Delta M = M_{K05} - M_{S04}$ between the M_{K05} and M_{S04} series is shown in Figure 2a together with errors of M_{S04} (uncertainties of M_{K05}, which are much smaller, are not included). The two

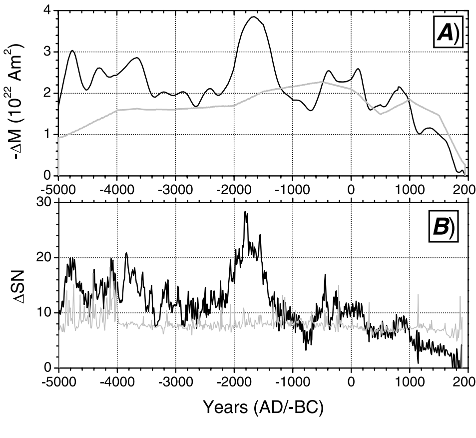

Figure 2. (a) Difference (solid curve) $-\Delta M = M_{S04} - M_{K05}$ between two geomagnetic series shown in Figure 1a, together with the 1σ uncertainty of the M_{S04} data set (grey shading). (b) Difference (solid curve) $\Delta SN = SN_{K05} - SN_{S04}$ between the sunspot number reconstructions shown in Figure 1c, together with the 1σ uncertainties of SN_{S04} (grey shading).

series are more or less close to each other after 1000 AD but the difference is sizeable before that. Importantly, ΔM is systematic and it is comparable to the 1σ error bars at most times. This agrees with the explanation proposed by *Korte and Constable* [2005a] that most of the difference can be attributed to the non-dipole influence in the VADMs caused by a strong regional bias in data distribution. We note the period 2000–1500 BC when the difference was very large, about $4 \cdot 10^{22}$Am^2 or 40%.

[8] In the following Section we evaluate how the new DM series M_{K05} can affect reconstructions of solar activity.

3. Solar Activity Reconstruction

[9] The reconstruction of solar activity presented here uses the new DM series by *Korte and Constable* [2005a], but is otherwise identical to that by *Solanki et al.* [2004]. It employs the same physics-based model, as briefly described below (see full details given by *Usoskin et al.* [2003, 2004] and *Solanki et al.* [2004]).

[10] The reconstruction starts from the decadal ^{14}C production rate Q computed by *Usoskin and Kromer* [2005] from the INTCAL98 compilation series [*Stuiver et al.*, 1998] of Δ^{14}C data in tree rings. This Q–series is consistent with other estimates of the ^{14}C production rate obtained by other groups [*Stuiver*, 1980; *Stuiver and Quay*, 1980; *Goslar*, 2001]. The used time series Q is shown in Figure 1b together with its long term trend (the best fit 4th order polynomial). One can see that, while there is a general long-term agreement between the dipole moment and Q, fine details are not synchronized.

[11] The global ^{14}C production rate Q is related to the cosmic ray flux at 1 AU via

$$Q = \int_{\theta=0}^{\pi} \int_{P_c(\theta,M)}^{\infty} J(P,\phi) Y(P) dP \sin\theta d\theta, \qquad (1)$$

where θ is the geomagnetic co-latitude and $P_c(\theta, M)$ is the local cosmic ray rigidity cutoff which depends on θ and dipole moment M. $J(P, \phi)$ is the differential cosmic ray rigidity spectrum near Earth, and ϕ is the modulation potential, which defines the shape of the cosmic ray spectrum $J(P)$ in a simple force-field approximation [*Usoskin et al.*, 2005]. $Y(P)$ is the differential yield function [*Castagnoli and Lal*, 1980] of ^{14}C, and P is the rigidity of primary cosmic rays. The cosmic ray transport model connects the heliospheric modulation potential ϕ to the Sun's open magnetic flux [*Usoskin et al.*, 2002], which in turn is linked with the magnetic flux in sunspots [*Solanki et al.*, 2000, 2002]. Thus, from the measured ^{14}C data one can reconstruct sunspot activity in the past. Note that, while the dipole moment M enters equation (1) implicitly (via the cutoff rigidity), it significantly affects the relation between Q and ϕ [*Frank*, 2000].

[12] Figure 1c shows the sunspot activity reconstructed by means of this method but using two different geomagnetic DM estimates, M_{S04} and M_{K05} (called henceforth SN$_{S04}$ and SN$_{K05}$, respectively). The solid curve based on M_{S04} is identical to that published by *Solanki et al.* [2004]. The difference ΔSN between the two reconstructions is shown in Figure 2b together with the error bars of the *Solanki et al.* [2004] reconstruction [*Solanki et al.*, 2004, supplementary material]. One can see that the new SN$_{K05}$ series is systematically higher than SN$_{S04}$ due to the systematically lower M. The value of ΔSN is consistent with the 1σ error bars after 1000 BC, i.e., for the last 3000 years, and is on average about 1.5σ higher for the period before 2000 BC. Between ca. 2000 and 1500 BC, the difference becomes large, exceeding 20 in sunspot numbers, which corresponds to 3σ. This period coincides with the largest deviation between the M_{S04} and M_{K05} series. Roughly, the relation between ΔSN and ΔM can be approximated as $\Delta\text{SN} = -5.329\ (\Delta M/10^{22}\ \text{Am}^2)$.

[13] The most direct test of the SN reconstruction is to confront the reconstructed sunspot numbers with actually observed values. Direct sunspot observations are available since 1610 [*Hoyt and Schatten*, 1998] in terms of group sunspot number, GSN, and a detailed comparison between SN$_{S04}$ and GSN, which has been performed by *Solanki et al.* [2004], shows a good correlation $r = 0.93$. The difference between the two M–series is small after 1610 (Figure 2b), and accordingly SN$_{K05}$ is nearly identical to SN$_{S04}$ (correlation between them is 0.99, and between SN$_{K05}$ and GSN it is 0.93). Thus, this direct test confirms the reliability of the SN reconstruction but cannot distinguish between the two geomagnetic series.

[14] We note that one can implicitly test whether the geomagnetic effect has been correctly removed by comparing the final SN-series with the M-series. Generally, no correlation is expected between sunspot numbers and geomagnetic dipole moment variations. SN$_{S04}$ and the used M_{S04} are not correlated, the cross-correlation coefficient is $r = 0.08 \pm 0.28$, in agreement with the above expectation. However, SN$_{K05}$ shows a small degree of negative correlation with M_{K05} $r = -0.23 \pm 0.26$. The latter suggests that there might be some discrepancy, but the insignificance of this residual correlation (confidence level about 0.5) does not allow us to reliably distinguish between the SN reconstructions obtained from the two geomagnetic series.

4. Long-Term Solar Activity

[15] The SN reconstruction performed here allows the fraction of time to be estimated that the Sun spends in grand minima of activity. As a grand minimum we consider here the period when the average sunspot number was not higher than 10 during at least two consecutive decades. According to the actual GSN data, the Sun spent about 18% of the time in the grand minimum state after 1610 AD. The SN$_{S04}$ reconstruction suggests that grand minima occupied about 13% of the time (920 years) since 5000 BC, and such grand minima were more or less evenly distributed in time with 350 years of grand minima duration during the last millennium (Maunder, Spörer, Wolf minima). The corresponding figure for the whole Holocene is about 12% (1360 years out of 11,400 years) [*Solanki et al.*, 2004]. The SN$_{K05}$ reconstruction yields a less frequent occurrence of grand minima, about 6% or 430 years after 5000 BC with 320 of these years occurring during the last millennium.

[16] It is also interesting to study the occurrence of grand maxima of activity. *Solanki et al.* [2004], using ^{14}C data, stated that the previous high activity episode, similar to the modern one, occurred 8000 year ago, i.e., around 6000 BC,

and the Sun spent on average about 10% of the time in a high activity state (the decadal sunspot number exceeding 60 during at least 2 consecutive decades). On the other hand, the SN reconstruction based on the *Korte and Constable* [2005a] palaeomagnetic series suggests that solar activity was high ca. 2200–1500 BC, reaching the modern level several times. The average fraction of time the Sun spends in the high activity state during the last 7000 years is higher, about 20%, according to the SN_{K05} reconstruction. Hyper-active episodes of sunspot activity (SN > 70, similar to the modern episode) remain very rare, however, being between about 1% (SN_{S04}) and 3% (SN_{K05}) of all the time during the last 7000 years. This estimate is in agreement with the estimate obtained from the full reconstructed series by *Solanki et al.* [2004], viz. the SN exceeds 70 in about 2% of the time during the Holocene. Thus, although the new geomagnetic series does affect the average level of the reconstructed sunspot activity, the conclusion that grand maxima similar to the modern high activity episode are rare is confirmed.

5. Conclusions

[17] Using the new series of the reconstructed palaeomagnetic dipole moment [*Korte and Constable*, 2005a], we have performed the full reconstruction of sunspot activity since 5000 BC and compared it with the previous reconstruction [*Solanki et al.*, 2004].

[18] Although the new reconstruction implies slightly higher sunspot activity during the studied period, it is consistent with the earlier results during most of the period under investigation. In particular, the conclusion that high activity episodes on millennium [*Usoskin et al.*, 2003] and multi-millennium [*Solanki et al.*, 2004] time scales are rare has been safely confirmed, in agreement with the ^{10}Be-based reconstructions [*McCracken et al.*, 2004]. According to the new reconstruction, the Sun was in a strongly active state, similar to the modern high activity episode with the decadal sunspot number systematically exceeding 70, only about 3% of the time during the last 7000 years, which is consistent with the estimate (2% of the time during the whole Holocene) based on our previous reconstruction [*Solanki et al.*, 2004]. The new SN reconstruction indicates that grand minima were rare before 1000 AD, while the previous reconstruction suggests that grand minima were more or less equally distributed over the millennia.

[19] In conclusion, although the new reconstruction of the dipole moment implies somewhat higher solar activity in the past, compared to all earlier data, the finding that the modern high level of solar activity is unusual is confirmed for the last 7000 years.

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