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For how long will the current grand maximum of solar activity persist?

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[1] Understanding the Sun's magnetic activity is important because of its impact on the Earth's environment. The sunspot record since 1610 shows irregular 11-year cycles of activity; they are modulated on longer timescales and were interrupted by the Maunder minimum in the 17th century. Future behavior cannot easily be predicted – even in the short-term. Recent activity has been abnormally high for at least 8 cycles: is this grand maximum likely to terminate soon or even to be followed by another (Maunder-like) grand minimum? To answer these questions we use, as a measure of the Sun's open magnetic field, a composite record of the solar modulation function Φ, reconstructed principally from the proxy record of cosmogenic ^{10}Be abundances in the GRIP icecore from Greenland. This Φ record extends back for almost 10,000 years, showing many grand maxima and grand minima (defined as intervals when Φ is within the top or bottom 20% of a Gaussian distribution). We carry out a statistical analysis of this record and calculate the life expectancy of the current grand maximum. We find that it is only expected to last for a further 15–36 years, with the more reliable methods yielding shorter expectancies, and we therefore predict a decline in solar activity within the next two or three cycles. We are not able, however, to predict the level of the ensuing minimum. **Citation:** Abreu, J. A., J. Beer, F. Steinhilber, S. M. Tobias, and N. O. Weiss (2008), For how long will the current grand maximum of solar activity persist?, *Geophys. Res. Lett.*, *35*, L20109, doi:10.1029/2008GL035442.

1. Introduction

[2] Explosive events on the Sun, such as flares and coronal mass ejections, which are manifestations of solar magnetic activity, have an important impact on the heliosphere. They are the source of energetic particles, which are a hazard in space, and give rise to magnetic storms that interfere with communications both in space and on the ground. It is therefore necessary to understand the origin of the Sun's cyclic activity, and – if possible – to predict its future course. The solar cycle is driven by an oscillatory hydromagnetic dynamo in the Sun's interior [e.g., *Tobias and Weiss*, 2007]. As yet there is no realistic numerical model of this nonlinear dynamo, and only parameterized mean-field models are available. Predictions, even of the peak level of the next cycle, are notoriously controversial [see *Schüssler*, 2007, and references therein]. Attempts using plausible, yet poorly constrained, mean-field dynamo models yield widely disparate forecasts [*Dikpati et al.*, 2006; *Choudhuri et al.*, 2007] demonstrating the sensitivity of such forecasts to details of the model and assumptions [*Bushby and Tobias*, 2007]. An alternative approach is to use precursor methods, based for example on measurements of the Sun's polar field or the geomagnetic *aa* index [e.g., *Schatten*, 2005; *Hathaway and Wilson*, 2006], or else to rely on timeseries analysis, utilizing either neural networks, attractor reconstruction or statistical methods [e.g., *Sello*, 2001; *Lundstedt*, 2006]. These difficulties in prediction are paralleled by those faced by meteorologists attempting to predict the next day's weather.

[3] One can also examine the record of solar activity since the invention of the telescope, as measured by the sunspot number R (e.g., http://sidc.oma.be/sunspot-data/). Quite what one might then predict for the next cycle depends on the length of the past record that one chooses to examine. If one takes into account only the last half dozen cycles then one would predict an increase in the level of activity. If instead one takes the record back to the beginning of the 18th century one recognises that the eleven year (Schwabe) cycle is modulated on a longer ~90 years (Gleissberg) timescale, and one would therefore forecast a decrease in activity; indeed, there are suggestions, both from the activity record and from measurements of total solar irradiance [*Lockwood and Fröhlich*, 2007], that this decline has already begun. However, the seventeenth century saw the occurrence of the Maunder minimum, when sunspots virtually disappeared [*Ribes and Nesme-Ribes*, 1993], and one is also led to ask whether such a catastrophic drop in activity might recur in the immediate future.

[4] Although there are no reliable records of sunspot activity prior to 1610, there are – fortunately – alternative proxy records that extend back for tens of thousands of years into the past. Galactic cosmic rays impinging on the Earth's atmosphere give rise to the production of cosmogenic radioisotopes such as ^{10}Be and ^{14}C. Cosmic rays are deflected by magnetic fields in the heliosphere and their incidence and hence the production rates of these isotopes are modulated by changes in solar magnetic activity. Variations in production rates of ^{14}C and ^{10}Be have been determined precisely for the last 10,000 years [*Stuiver and Braziunas*, 1988; *Vonmoos et al.*, 2006]. Recurrent grand minima interspersed with grand maxima feature throughout both of these records.

[5] Our aim in this paper is to carry out a statistical analysis of the ^{10}Be record that enables us to estimate the future duration of the current grand maximum and to predict the likelihood of a subsequent grand minimum. A different approach, using the ^{14}C record to reconstruct sunspot numbers, has been followed by *Solanki et al.* [2004] and *Usoskin et al.* [2006, 2007]. In the next section we introduce the solar modulation function Φ as the relevant measure of solar magnetic activity and describe the record derived from

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the GRIP ice-core in Greenland, which extends over 9000 years with a mean temporal resolution of about 5 years. In section 3 we carry out a statistical analysis of the data and then summarise our conclusions in the final section.

2. Solar Modulation Function From the GRIP ^{10}Be Record

[6] The record that best represents the role of open solar magnetic fields in deflecting cosmic rays is the solar modulation function Φ, which can be derived from either the ^{10}Be or the ^{14}C production rates after correcting for variations in the geomagnetic field [see, e.g., *Vonmoos et al.*, 2006; *Usoskin et al.*, 2007]. Figure 1a shows the GRIP timeseries for Φ from 9313 to 354 BP (7363 BC to 1596 AD). This primary data-set has been subjected to smoothing with a binomial filter over 61 points, which corresponds approximately to a 40-year low-pass filter and eliminates the basic Schwabe cycle. It is apparent that there are many grand minima and maxima in this record. Frequency analysis reveals the presence of a number of significant periodicities, namely around 200 years (de Vries) and 2300 years (Hallstatt) [*Tobias et al.*, 2004]. In order to extend this record up to the present, we have constructed a composite timeseries Φ (t) by combining the GRIP record with the ^{10}Be record from the South Pole spanning the interval from 1619 to 1950 (which has itself been filtered using a 22 year running mean) [*McCracken et al.*, 2004] and the record derived from direct measurements of cosmic rays by neutron monitors from 1950 to 2004 [*Usoskin et al.*, 2005] (see Figure 1b). The latter records have been corrected to take account of the different Local Interstellar Spectrum Models that had been adopted and to ensure compatibility with the Local Interstellar Spectrum Model that was used to obtain the GRIP timeseries [*Steinhilber et al.*, 2008].

[7] Inspection of Figure 1a indicates a long period trend which may contain climatic and geomagnetic components. This may be the cause of the slight divergence of the ^{10}Be from the ^{14}C reconstructions in the early parts of the records [*Vonmoos et al.*, 2006]. We therefore remove this linear trend from the composite data-set and add a constant offset so that the time series matches the accurately determined value of Φ for 2004. We then impose a high-pass filter to remove periods longer than 3000 years, together with a 40 year low-pass filter. The most recent part of the composite filtered data-set is shown in Figure 2a. This record shows a marked double-hump structure which corresponds to the sunspot maxima around 1960 and 1980–1990. It is worth noting that in this composite reconstruction of the modulation function the current grand maximum in activity (with $\Phi \approx$ 700 MeV) is by no means unique – it has been exceeded three times in the past thousand years [*McCracken et al.*, 2004] – in contrast to some reconstructions of R itself [*Solanki et al.*, 2004; *Usoskin et al.*, 2007].

[8] In this filtered record the variable Φ is normally distributed, as shown by Figure 2b, with a mean of 478 MeV and a standard deviation of 174 MeV. The definition of a grand extremum is arbitrary, provided that the Maunder minimum appears as a grand minimum. We choose to adopt the following criterion: the variable Φ should spend 60% of the time outside grand extrema, with 20% in grand maxima and 20% in grand minima. It follows then that a grand minimum is an event with $\Phi \leq \Phi_{min}$ = 340 MeV, while a grand maximum is an event with $\Phi \geq \Phi_{max}$ = 616 MeV. These levels are indicated as dashed lines in Figure 2. Note that the Dalton minimum (at 1810) just survives.

[9] Inspecting the records in Figures 1a and 2, we observe that grand maxima and grand minima have a characteristic timespan of twenty to sixty years [cf. *Steinhilber at al.*, 2008], and so we might naively predict that the current grand maximum, which has already lasted around eighty years, will terminate soon. The next section will contain a precise statistical analysis of the distributions in order to obtain an expected lifetime for this grand maximum.

3. Statistical Analysis

[10] Figure 3a is a scatter-plot of the durations of the 66 grand maxima in the record, ordered from the most recent to the earliest. We see immediately that all but two of these have a duration of less than 80 years. The longest, with a duration of 95 years, occurred around 300 AD and is apparent in Figure 2a. The binned distribution for the lengths of maxima is shown as the heavy line in Figure 3b. Since the current grand maximum has already lasted for 80 years, it is not possible to make a very precise statement directly from the distribution, owing to the paucity of data at its high end. However, if the current maximum lasted for two more solar cycles then it would be the longest such event in the past 10,000 years. Is that likely? We answer this question by fitting the data to appropriate statistical distributions and calculating the life expectancy of the current grand maximum. Two statistical distributions are good candidates for this purpose [*Ryan and Sarson*, 2007], the gamma distribution and the lognormal distribution. We estimate the parameters for the gamma distribution

$$f(x; a, b) = \frac{x^{a-1} \exp(-x/b)}{b^a \Gamma(a)}, \qquad (1)$$

using the maximum likelihood method, to be a = 2.20, b = 13.13. Binned values for this distribution are also shown in Figure 3b. We carry out a χ^2 goodness of fit test on the binned distributions and find that the fit is highly significant at the 5% level. From this gamma distribution we find that the life expectancy of the current grand maximum, given its present duration, is 95 years, i.e. it is expected to end in fifteen years. Note that such a prediction is relative to given filtered data as well as to our arbitrary definition of a grand extremum. If Φ_{max} is lowered (raised) then the life expectancy will be increased (decreased): for instance, if we were to set Φ_{min} = 400 MeV and lift Φ_{max} to 556 MeV then the current lifetime would be 87 years, with a remaining life expectancy of 14 years.

[11] There are two sources of error in these predictions. Each of the original data points for Φ has an estimated error of 10% [*Vonmoos et al.*, 2006] but these errors are dominated by those introduced by fitting a gamma distribution. The 95% confidence intervals for a and b are (1.60, 3.02) and (9.18, 18.79), respectively. Using a Monte Carlo technique, we estimate that the resulting rms error in the life expectancy is 3 years. We have also confirmed that the

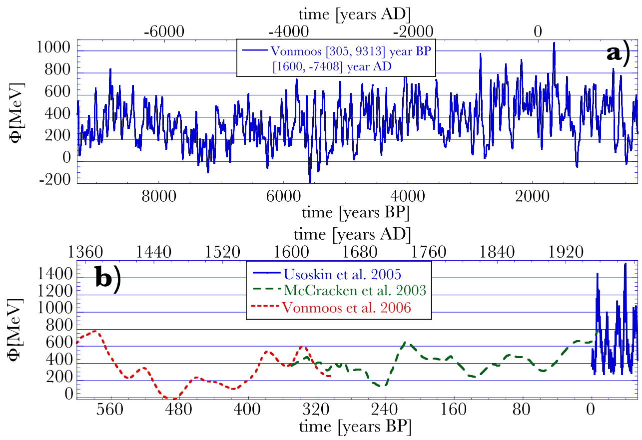

Figure 1. Records of solar activity. (a) Timeseries for Φ constructed from the GRIP ice-core and filtered to eliminate the 11 year Schwabe cycle [*Vonmoos et al.*, 2006]. (b) Composite timeseries showing the modulation potential Φ, after compensating for the use of different Local Interstellar Spectrum (LIS) models [*Steinhilber et al.*, 2008]. Shown are the smoothed annual means of Φ from the GRIP ice-core (red), from the South Pole (green), and the annual means from direct measurement of cosmic rays.

remaining life expectancy is not significantly altered if the 40-year low-pass filter is replaced by a 60-year low-pass filter, or if the high-pass filter is omitted. Thus these estimates, based on a gamma distribution, are apparently robust.

[12] We have carried out a similar procedure for the lognormal distribution, which is also shown in Figure 3b. The fit for this distribution is less satisfactory than for the gamma distribution, as is obvious from Figure 3b, and is barely significant at the 5% level. The corresponding life expectancy for this poorly matched case is 116 years, with an estimated error of about 7 years. Thus we have estimates

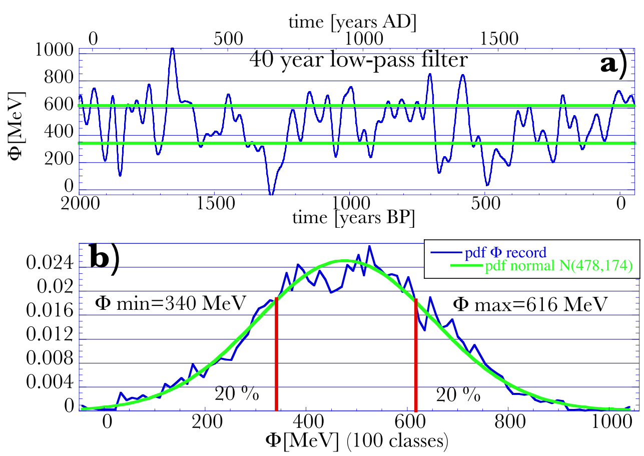

Figure 2. (a) Section of the filtered composite timeseries for the modulation potential Φ, after imposing a 3000 year high pass filter and a 40 year low-pass filter. (b) Probability distribution for the measured values of the modulation potential Φ, compared with a normal distribution. The data are normally distributed about a mean 477.8 MeV and standard deviation 174 MeV.

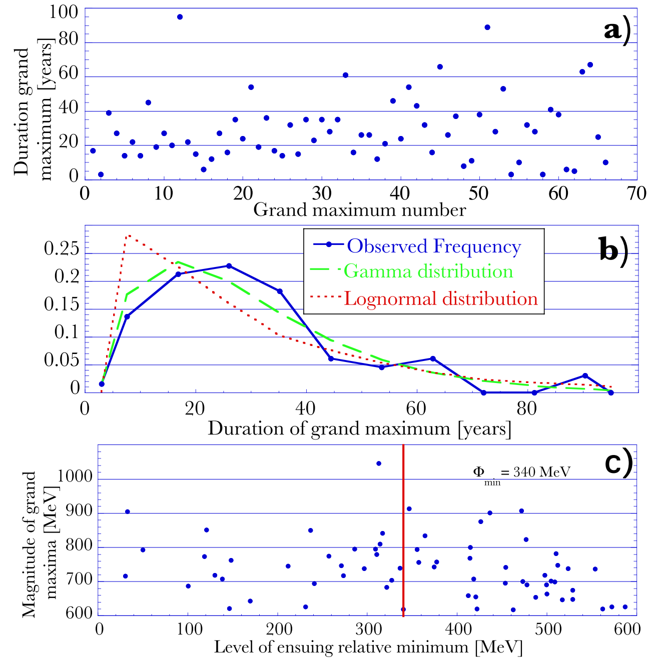

Figure 3. Distribution of the durations of grand maxima in activity. (a) Scatter plot for durations of grand maxima, listed consecutively back in time. Note that there are only two examples with durations longer than that of the current grand maximum. (b) Binned distribution for durations of grand maxima. Superimposed are the fitted gamma (green) and lognormal (red) distributions. (c) Scatter plot relating the level of a grand maximum in Φ (as ordinate) to that of the subsequent relative minimum. Grand minima lie to the left of the heavy vertical line. No significant correlation is visible in the data.

of the remaining lifetime of the current grand maximum that range from fifteen to thirty-six years, based on these statistical tests.

[13] Given the relatively short timescale associated with the ending of the current grand maximum we may ask how deep the next relative minimum is likely to be, and speculate whether it will be deep enough to qualify as a grand minimum. Figure 3c shows a scatter-plot of the level of each grand maximum in the filtered Φ record versus that of the subsequent relative minimum. Clearly there is no correlation between these variables and so it is impossible to make any precise predictions for the depth of the ensuing minimum. We can only infer that there is a 40% probability that the current grand maximum will actually be succeeded by a grand minimum. Our treatment here has focused on the history of the solar modulation function Φ, as derived from the ^{10}Be record. While these results agree qualitatively with those of *Solanki et al.* [2004] and *Usoskin et al.* [2007], direct comparison is not straightforward because of the different data-sets used, different definitions of grand maxima and different filtering techniques applied. These authors likewise find that the current grand maximum has lasted unusually long (65 years) and they expect that it will terminate within the next half-century. They compare the distribution of the sunspot number *R* with a normal distribution and fit both power law and exponential distributions

to the durations of grand maxima and grand minima, as well as to the intervals between them. We consider that the gamma distribution is more appropriate and, unlike them, we have gone on to predict the life expectancy of the current episode of extreme activity.

4. Conclusion

[14] We have attempted to estimate the future life expectancy of the current grand maximum in solar magnetic activity using three methods: visual inspection of the data, comparison with the duration of the longest maximum and, most reliably, estimation from two different statistical distributions. Although there is some scatter in our estimates of the future life expectancy, all three methods predict that this bout of enhanced activity will not last longer than two or three cycles, with the more reliable methods giving shorter predictions. We therefore expect that the current grand maximum will come to an end within the next few solar cycles. If the next maximum of the Schwabe cycle (around 2012) continues the downward trend of its predecessors then the message will be clear. Although it is possible that the activity level will just cross the threshold for being considered a grand maximum, to return almost immediately, we consider it more likely that the level of activity will either regress to the mean or plunge into the next grand minimum. We await the outcome with keen interest. If it turns out that there is a precipitate decline in solar magnetic activity, it may be expected to have a slight cooling effect on the earth's atmosphere; this will, however, be insignificant compared with the global warming caused by greenhouse gases.

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