Presence of the solar de Vries cycle (205 years) during the last ice age

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Presence of the solar de Vries cycle (~205 years) during the last ice age

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Abstract. Certain characteristic periodicities in the $\Delta^{14}C$ record from tree rings, such as the well-known 11-yr Schwabe cycle, are known to be of solar origin. The origin of longer-period cycles, such as the 205-yr de Vries cycle, in the $\Delta^{14}C$ record was less certain, and it was possible to attribute it either to solar or climatic variability. Here, we demonstrate that the de Vries cycle is present in ^{10}Be data from the GRIP ice core during the last ice age (25 to 50 kyr BP). Analysis of the amplitude of variation of this cycle shows it to be modulated by the geomagnetic field, indicating that the de Vries cycle is indeed of solar, rather than climatic, origin.

1. Introduction

The detection of solar cycles in ice cores using the cosmogenic radionuclides has important consequences for three distinct areas of research. Solar physicists are interested in the long-term behaviour of the length and the amplitude of the cycles in order to understand the underlying mechanisms that drive the solar dynamo [*Beer et al.*, 1998]. Climatologists on the other hand compare climate records with long records of solar variability in order to investigate what role solar variability plays in climate change [*Beer et al.*, 2000, *Damon and Sonett*, 1991]. Furthermore, climatologists are interested in the detection of solar cycles in different climate records because if the average cycle length is constant, they provide a natural clock that can be used to date different climate archives [*Steig et al.*, 1998].

Analysis of the cosmogenic radionuclides ^{10}Be and ^{36}Cl in ice cores permits the examination of solar variability through the last 100 kyr or more, extending the $\Delta^{14}C$ record from tree rings [*Stuiver et al.*, 1998] by an order of magnitude. Several periodicities found in the $\Delta^{14}C$ data have been interpreted in terms of changing solar activity. These are the Gleissberg cycle (period of approximately 88 yr), the de Vries cycle (period of approximately 205 yr) and the Hallstatt cycle (period of approximately 2300 yr) [*Stuiver and Braziunas*, 1993, *Damon and Sonett*, 1991]. Preliminary results of spectral analysis of ^{10}Be profiles from the Dye 3 core (covering the last 550 yr) and the South Pole core (covering the last 1200 yr) suggest periodicities of about 90 and 200 yr [*Beer et al.*, 1994, *Raisbeck et al.*, 1990]. The well known 11-yr Schwabe cycle has been found in ^{10}Be records [*Steig et al.*, 1998, *Beer et al.*, 1990]. It is difficult to observe the Schwabe cycle in the $\Delta^{14}C$ data, because the amplitudes of short-term production changes are strongly attenuated due to the large sizes of the carbon reservoirs (atmosphere, biosphere and ocean). The solar origin of the Schwabe and the Gleissberg cycle signals in the proxy data is strongly supported by the historical sunspot record. The solar origin of the de Vries cycle is less well established due to lack of direct observational data. A solar relationship is suggested by the fact that maxima of the de Vries cycle in the $\Delta^{14}C$ data coincide with the Maunder (AD 1645-1715) and Spörer (AD 1420-1540) minima [*Damon and Sonett*, 1991, *Eddy*, 1976] of solar activity. The reconstruction of the long-term solar variability is not only fundamental to increasing our understanding of the solar dynamo, but also in determining the role of solar forcing in past and present climate changes [*Beer et al.*, 2000]. A possible solar forcing of climate change has been suggested by the coincidence of low $\Delta^{14}C$ values (Grand Maximum) with the "Medieval Warm Epoch" of the 11th through 13th centuries in western Europe. Further, the Maunder Minimum and the Spörer Minimum, which coincide with high $\Delta^{14}C$ values, fit with severe temperature dips during the Little Ice Age (14th to 19th centuries) [*Eddy*, 1976]. However new temperature reconstructions [*Mann et al.*, 1999] lead one to the question whether the "Medieval Warm Epoch" was a phenomenon that occured all over the Northern

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Hemisphere. The de Vries cycle has been found e.g. in the tree ring widths [*Sonett and Suess,* 1984] of high altitude Bristelcone pines dated from 3405 yr BC to 1885 yr AD and in the thermoluminescence record from a sea sediment covering the last 2500 yr [*Cini Castagnoli et al.,* 1998]. These findings provide further evidence of a link between changing solar activity and climate on time scales of several thousands of years. Considering only the $\Delta^{14}C$ data it cannot be completely ruled out that the de Vries cycle is of climatic origin, in particular that it is due to changes of the carbon cycle. To separate climatic from production effects, it is useful to compare time series of ^{10}Be and $\Delta^{14}C$, because the relative production rate changes of these two isotopes due to solar and geomagnetic modulation are similar [*Masarik and Beer,* 1999, *Lal and Peters,* 1967], whereas their transport behaviour in the atmosphere is different [*Bard et al.,* 1997, *Beer et al.,* 1994]. ^{10}Be becomes fixed to aerosols and is washed out from the atmosphere by precipitation within about a year [*Raisbeck et al.,* 1981]. In contrast, ^{14}C is oxidised to $^{14}CO_2$ and starts exchanging between atmosphere, biosphere and ocean [*Siegenthaler et al.,* 1980]. Due to its relatively long atmospheric residence time it is well homogenised in the atmosphere. For a comparison of ^{10}Be and $\Delta^{14}C$, the high-resolution ^{10}Be data from the GRIP ice core provide an excellent data record for the last 100 kyr [*Yiou et al.,* 1997a]. However, so far we have only analysed a continuous profile of ^{10}Be concentrations in the GRIP ice core for the last ice age, and not as yet for the last 10 kyr BP, which are covered by the $\Delta^{14}C$ data. Nevertheless it is possible to compare the ^{10}Be and $\Delta^{14}C$ records by considering their power spectra.

2. Data

The ^{10}Be concentration data from the GRIP ice core are based on ice samples of 55 cm length. In the time interval from 25 to 50 kyr BP, this corresponds to a mean time resolution of about 45 yr. Figure 1 shows in the upper panel the ^{10}Be concentration record as a function of time, using the depth age relation suggested by *Johnsen et al.* [1995]. The

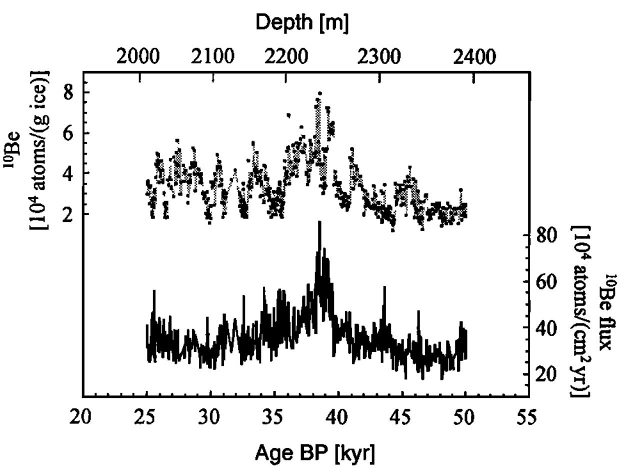

Figure 1. ^{10}Be concentration and ^{10}Be flux as a function of age and depth for the time interval 25 to 50 kyr BP. The time scale and the used accumulation rate is based on the suggestions of *Johnsen et al.* [1995]. Note that the depth scale is not linear.

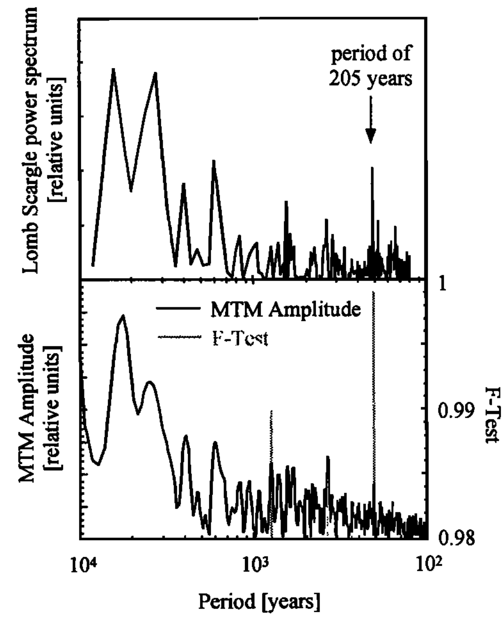

Figure 2. a) Lomb Scargle [*Scargle,* 1982; *Haubold and Beer,* 1992] power spectrum of the ^{10}Be flux in the time interval 25 to 50 kyr BP. b) Multitaper Method (MTM) harmonic analysis of the ^{10}Be flux. The parameter values are $N\Omega = 8$ (bandwidth), $K = 10$ (tapers). The left axis is the estimated MTM Amplitude (solid line) and the right axis is the statistical F-test (dotted line).

^{10}Be concentration in the GRIP ice core is the result of the interplay between production, transport and deposition. To compensate for changes in the ice accumulation rate the ^{10}Be concentrations were converted into fluxes (Figure 1) using the accumulation rate given by *Johnsen et al.* [1995].

3. Results and Discussion

The spectral analysis of the ^{10}Be flux record using the Lomb Scargle technique [*Haubold and Beer,* 1992, *Scargle,* 1982] is shown in Figure 2 a. The de Vries cycle is one of the most prominent periodicities in the ^{10}Be data, comparable to the power spectrum of the $\Delta^{14}C$ data [*Stuiver and Braziunas,* 1993]. After applying linear interpolation to produce equally spaced ^{10}Be flux data, other spectral analysis methods such as FFT (Fast Fourier Transformation), MEM (Maximum Entropy Method) and MTM (Multitaper Method) confirm the dominant period of 205 ± 5 yr obtained with the Lomb Scargle method. Figur 2 b shows the spectral analysis of the ^{10}Be flux using the MTM technique [*Yiou et al.,* 1997b, *Paillard et al.,* 1996]. A statistical F-test performed on the MTM amplitude shows that the de Vries cycle is significant on the 99 % level. To exclude the possibility that the spectral analysis of the ^{10}Be flux only shows the de Vries cycle due to a periodicity in the accumulation rate of approximately 205 yr (^{10}Be flux $\cong$ ^{10}Be concentration * snow accumulation rate), we repeated the spectral analysis for the ^{10}Be concentration data. The de Vries cycle is also present in the ^{10}Be concentration data, which strengthens our result. Nevertheless in this paper we refer to the ^{10}Be flux, because it is a better proxy of the ^{10}Be production rate.

Having identified the de Vries cycle in the ^{10}Be data, we now address the question of whether this cycle is of solar or climatic origin. If it is of solar origin its amplitude should be modulated by the geomagnetic field. However amplitude modulation by the geomagnetic field is not expected if the de Vries cycle is of climatic origin. The dependence of the ^{10}Be production rate on the geomagnetic field and on the solar activity has been calculated by *Masarik and Beer* [1999]. Figure 3 shows the mean global production rate of ^{10}Be as a function of the geomagnetic field intensity and the solar activity. The solar activity is described by the solar modulation parameter Φ ($\Phi = 0$ MeV corresponds to a quiet and $\Phi \geq 1000$ MeV to a very active sun) [*Masarik and Beer*, 1999]. Figure 3 also shows that for a constant solar activity the production rate of ^{10}Be increases with decreasing geomagnetic field intensity. For example, a reduction of the geomagnetic field intensity from its present value to zero would increase the production rate of ^{10}Be by a factor of 2.7 for $\Phi = 0$ MeV and 1.8 for $\Phi = 1000$ MeV, respectively. Moreover Figure 3 shows that for a fixed variation of the solar modulation parameter a lower geomagnetic field intensity leads to a greater amplitude in the ^{10}Be production signal than a higher field intensity. For example a change of the solar modulation parameter from $\Phi = 1000$ MeV to $\Phi = 0$ MeV leads to a 3.8 times larger change in the production rate if the geomagnetic field is reduced from the present value to zero.

We now investigate how well these theoretical considerations agree with the experimental data. Assuming that the ^{10}Be flux reflects the mean global ^{10}Be production rate [*Wagner et al.*, 2000, *Steig et al.*, 1996, *Beer et al.*, 1990] and using published paleogeomagnetic field variations [*Laj et al.*, 2000; *Tric et al.*, 1992] the geomagnetic modulation effect on the de Vries cycle can be investigated. Support for this assumption is based on the fact that central Greenland receives a substantial part of its precipitation from lower latitudes [*Johnsen et al.*, 1989] and many chemical species found in the ice originate from eastern Asia [*Biscaye et al.*, 1997]. The main trends of the geomagnetic field intensity during the last ice age are fairly well known. In the lower panel of Figure 4 two estimations of the paleogeomagnetic field intensity relative to the level of today are shown, which are based on remanence measurements from six sediment

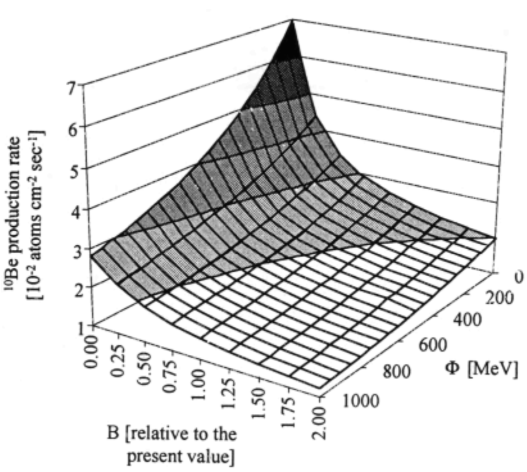

Figure 3. Dependence of mean global ^{10}Be production rate on the relative geomagnetic field intensity B [normalised to present intensity] and on the solar modulation parameter Φ [MeV].

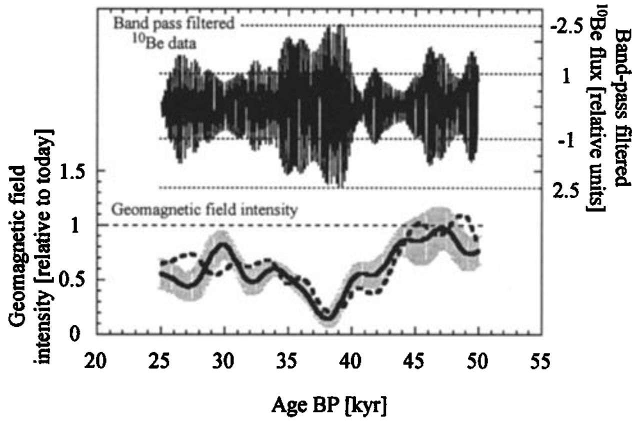

Figure 4. Upper panel: Band pass filtered ^{10}Be flux [$(215\ yr)^{-1} \leq \tau \leq (195\ yr)^{-1}$] [*Paillard et al.*, 1996] over the time period of 25 to 50 kyr BP. Lower panel: paleomagnetic field intensities during the last ice age: The first (dotted line) is derived from remanence measurements of several Mediterranean sediment cores [*Tric et al.*, 1992]. The second (solid line) is based on remanence measurements of several North Atlantic sediment cores [*Laj et al.*, 2000]. The shaded area corresponds to the $\pm 2\ \sigma$ uncertainties. Both records are low pass filtered (cut off frequency = 1/3 kyr^{-1}) to obtain a comparable time resolution as the envelope of the band pass filtered ^{10}Be flux.

cores of the North Atlantic [*Laj et al.*, 2000] and from four sediment cores of the Mediterranean sea [*Tric et al.*, 1992]. The North Atlantic PaleoIntensity Stack since 75 ka (NAPIS-75) [*Laj et al.*, 2000], originally placed on the GISP2 time scale [*Grootes et al.*, 1997] is transferred to the GRIP time scale [*Johnsen et al.*, 1995] by synchronising the $\delta^{18}O$ records. The paleogeomagnetic field intensity record based on the Mediterranean sediments is transferred to the GRIP time scale as described in *Wagner et al.* [2000]. The minimum of the geomagnetic field intensity at about 38.5 kyr BP corresponds to the so called Laschamp event. Figure 4 shows in the upper panel the band pass filtered ^{10}Be flux with a frequency range between $(215\ yr)^{-1}$ and $(195\ yr)^{-1}$. During the minimum of the magnetic field at about 38.5 kyr BP the amplitude of the de Vries cycle is about twice as high as during time periods, when the geomagnetic field intensity is approximately equal to today. The shared variance (r^2) between the envelope of the amplitude of the band pass filtered ^{10}Be signal and the geomagnetic field data is 30 % for the NAPIS-75 record and 33 % for the Mediterranean record, which is significant on the 99 % level. After low pass filtering the envelope of the amplitude with the same cut off frequency $(3\ kyr)^{-1}$ as the geomagnetic field data were low pass filtered, the shared variances increase to values of about 40 %. Taking into account that the amplitude of solar activity cycles changes with time (e.g. sun spot cycle) [*Beer et al.*, 2000, *Beer et al.*, 1998], a shared variance of 30 – 40 % can be considered as high.

This geomagnetic modulation of the amplitude of the de Vries cycle strongly points to a solar origin of the periodicity of approximately 205 yr in the ^{10}Be flux. In addition the presence of the de Vries cycle in the GRIP ice core confirms that the relative time scale between 25 and 50 kyr BP is precise.

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