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Variations in solar magnetic activity during the last 200 000 years: is there a Sun–climate connection?

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Abstract

The production of ^{10}Be in the Earth's atmosphere depends on the galactic cosmic ray influx that, in turn, is affected by the solar surface magnetic activity and the geomagnetic dipole strength. Using the estimated changes in ^{10}Be production rate and the geomagnetic field intensity, variations in solar activity are calculated for the last 200 ka. Large variations in the solar activity are evident with the Sun experiencing periods of normal, enhanced and suppressed activity. The marine $\delta^{18}O$ record and solar modulation are strongly correlated at the 100 ka timescale. It is proposed that variations in solar activity control the 100 ka glacial–interglacial cycles. However, the ^{10}Be production rate variations may have been under-estimated during the interval between 115 ka and 125 ka and may have biased the results. Future tests of the hypothesis are discussed.

Keywords: solar activity; climate change; Be-10; cosmogenic elements; magnetic field; Milankovitch theory; solar cycles

1. Introduction

The way the solar surface magnetic activity affects the Earth's climate on short timescales (days through centuries) constitutes an area of active research [1] with postulated mechanisms that include: (1) changes in solar luminosity as the Sun becomes magnetically more active [2–5], and (2) variations in solar activity leading to large changes in solar ultraviolet radiation [6] that, in turn, affects the stratospheric ozone content [7], and (3) modulated galactic cosmic rays influencing the cloud formation via inducing changes in the tropospheric ion production [8–10]. Evidence linking solar activity to climate change during the last millennium has also accumulated on a 100-yr timescale. Friis-Christensen and Lassen [11] report a close correspondence in the last 100 yr between average Northern Hemisphere temperatures and changes in the length of the solar magnetic cycle. An often-cited example is that of the Maunder Minimum (1645–1715 AD) corresponding to the Little Ice Age during which no sunspot activity was observed [12]. Using the combined ^{14}C and ^{10}Be records, a solar activity minimum has been inferred for this period centered at 1690 AD [13,14]. Other solar activity minima centered at 1060, 1320 (Wolf), 1500 (Spörer), and 1820 AD [14]. Also, the solar activity is inferred to be high during the Medieval Warm Period (12th and 13th centuries) [15,16]. On the basis of

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variations observed in the ^{14}C contents of tree rings and their growth, Suess and co-workers inferred that the solar activity varies with a 200-yr cycle [17,18], which also controls the climate [19]. Stuiver and Braziunas [20] investigated a 9600-yr-long high precision ^{14}C record and found that the Sun is oscillating with a fundamental frequency of 1/420 yr^{-1} with the second and third harmonics corresponding to 218- and 143-yr periods, respectively. These workers suggest that there may be a Sun–climate relationship for the third harmonic. A recent paper concludes that surface winds and surface ocean hydrography in the sub-polar North Atlantic have been influenced by 1500-yr oscillations in solar activity through the entire Holocene [21]. Does the solar activity also vary on a longer timescale? If so, what is its relationship to long-term climate change? In this paper I explore these two questions by estimating the relative variations in solar modulation of galactic cosmic rays (GCR), assuming that the modulation depends directly on the mean interplanetary magnetic field generated by solar surface magnetic activity (see a recent review [22]).

2. Theory

Variations in the solar surface magnetic field, which are carried out by the solar wind and stretch across the heliosphere, inversely modulate the intensity of the GCR incident on the heliospheric boundary (e.g., [22]). The cosmic ray particles reaching the Earth are further affected by the geomagnetic field, which deflects them depending on their energy and angle of incidence. For each angle of incidence there is a cut-off energy ('rigidity') below which the incoming particle cannot interact with the Earth's atmosphere. Modulation of GCR particles with energies above $\sim$1 GeV/nucleon leads to variations in the terrestrial production rates of cosmogenic radionuclides such as ^{14}C and ^{10}Be, formed due to the interaction of cosmic ray particles with atmospheric nitrogen and oxygen [23]. It follows that by determining the long-term variations in the production rates of cosmogenic radionuclides one can assess temporal changes in the solar surface magnetic activity, provided that the variations in geomagnetic-dipole strength for the same time period are known, a functional relationship between solar modulation of cosmic rays, geomagnetic-dipole strength and cosmogenic radionuclide production rate is available, and the GCR flux incident on the heliospheric boundary has remained constant over the time period of interest.

Due to its long half-life ($t_{1/2} = 1.5 \times 10^6$ yr) and relatively simple geochemical cycle [24,25], ^{10}Be is a cosmogenic radionuclide suitable for investigating the long-term variations in solar magnetic activity. Masarik and Beer [26] have theoretically calculated the global average production rate of ^{10}Be for discrete values of geomagnetic field strength and solar modulation. Fig. 1 shows the relationships between the global average production rate of ^{10}Be (Q), the geomagnetic field strength (M), and the solar modulation factor (ϕ) (data from J. Masarik). All parameters have been normalized to their present-day values (shown by subscript '0'). The data plot along a surface and show that the ^{10}Be production rate is inversely related to the geomagnetic field strength and the solar modulation factor, the latter being the energy lost by cosmic ray particles while traversing the heliosphere and reaching the Earth's orbit. There is a direct but not one-to-one relationship between the solar modulation factor and solar surface magnetic activity [23]. I approximate the global average production rate of ^{10}Be at a time 't' normalized to present-day by a product of two functions F and G that are independent of M and ϕ, respectively:

$$\left(\frac{Q_{M_t\phi_t}}{Q_{M_0\phi_0}}\right) = f\left(\frac{\phi_t}{\phi_0}, \frac{M_t}{M_0}\right) \approx F\left(\frac{\phi_t}{\phi_0}\right)_M \cdot G\left(\frac{M_t}{M_0}\right)_\phi \quad (1)$$

The data obtained through the empirical function thus fitted are plotted in Fig. 1 and show a general coherence with the data from Masarik, except when M/M_0 and ϕ/ϕ_0 are close to zero ($R^2 = 0.84$). This function permits us to assess the relative variations in solar modulation factor for any time in the past for which the average production rate of ^{10}Be and the geomagnetic dipole strength are available. In this paper I will

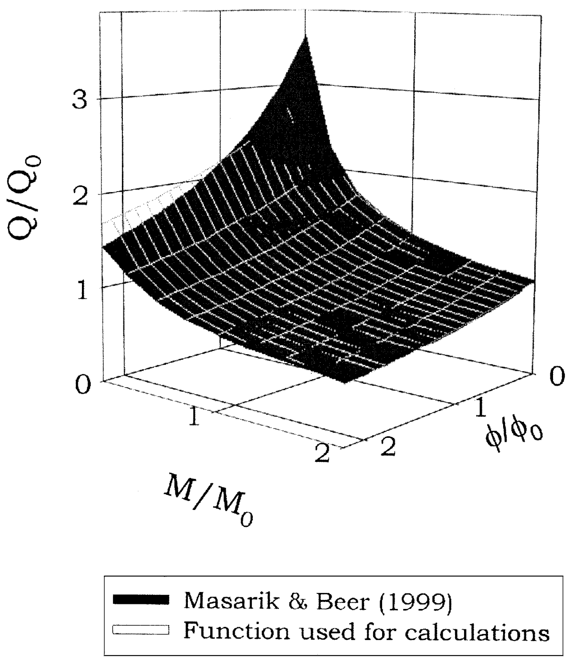

Fig. 1. A three-dimensional plot giving theoretically expected variations in the atmospheric ^{10}Be production rate as a function of solar modulation factor and geomagnetic field intensity (black surface) [26]. A nearly identical relationship can also be obtained using the data from Lal [23], but is not used here for calculations. As expected, the solar modulation and geomagnetic field intensity inversely affect the production rate. The data can be fitted to a function with explicit dependence of the production rate over solar modulation and geomagnetic field intensity (white mesh), with all parameters normalized to their respective present-day values. The function has the following form (see text):

$$\left(\frac{Q_{M_t\phi_t}}{Q_{M_0\phi_0}}\right) \approx \left[\frac{1}{a+b(\phi_t/\phi_0)}\right]\left[\frac{c+(M_t/M_0)}{d+e(M_t/M_0)}\right]$$

where the constants a–e were determined using the data provided by J. Masarik: $a = 0.7476$, $b = 0.2458$, $c = 2.347$, $d = 1.077$, and $e = 2.274$. This treatment permits calculation of normalized solar modulation at any time in the past for which the normalized ^{10}Be production rate and relative geomagnetic field intensity are specified.

estimate relative solar modulation for the last 200 ka, assuming that the above relationship holds for this time period by utilizing the existing compilations of past variations in ^{10}Be production rate and geomagnetic-dipole strength. In order to uniquely determine the variations in the solar magnetic activity, it is necessary that the established long-term production rates of ^{10}Be and corresponding variations in the geomagnetic-dipole strength are 'time-tuned' to each other and that neither of the records depends on parameters other than the ones described above. As discussed below, while the best existing dataset will be used for the calculation of solar modulation factor, high fidelity data strictly satisfying the above criteria are not yet available.

3. Data

3.1. Geomagnetic field intensity variations

Most reliable information on the prevailing geomagnetic field intensity comes from volcanic rocks. However, the volcanic rocks do not provide a continuous record. Continuous records have been obtained from the natural remanent magnetizations (NRM) of marine sediments [27–30]. The NRM signal of marine sediments can, however, be disturbed by variations in lithological parameters that are mostly climatically controlled. I will use an 800-ka synthetic record of relative variations in geomagnetic field intensity (Sint-800) that has been reconstructed from stacking the results of 33 marine sediment cores [30]. This record incorporates the results of an earlier shorter version extended to the last 200 ka (Sint-200 [29]). Using volcanic records of absolute field intensity data for the last 40 ka, this record has been converted to virtual axis dipole moments (VADMs). The Sint-800 shows an overall internal coherence and no stable periodicity, indicating that disturbances of the NRM signals in individual sediment cores were minimized [30]. This record does not provide data for the last 2 ka because the uppermost part of sedimentary records is not always reliable as it may be affected by coring (J. Guyodo, written communication, 2000). For this time period I will use the VADMs obtained from Hawaiian lavas [31]. Fig. 2a shows the relative geomagnetic field intensity normalized to present-day (M/M_0). The geomagnetic field intensity appears to have varied by a factor of three over the last 200 ka with three excursions when the intensity became less than half of the present value (Fig. 2a).

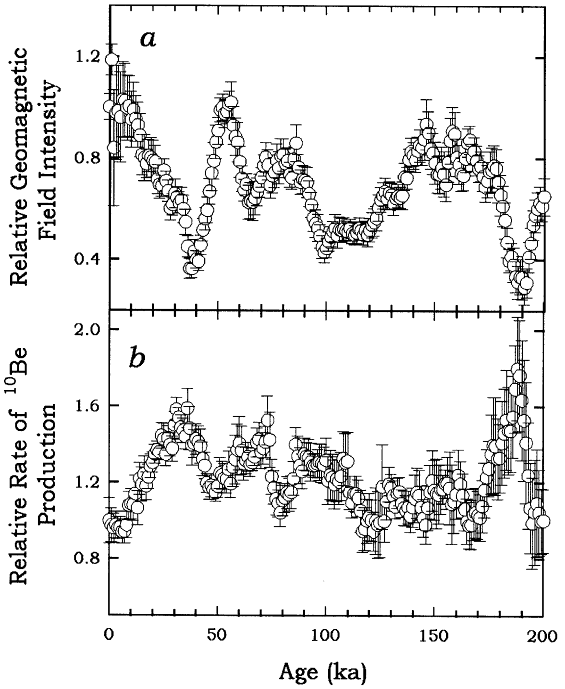

Fig. 2. (a) Globally stacked record of relative geomagnetic field intensity obtained from NRM of marine sediments (Sint-800) [30]. The record has been calibrated for the absolute paleomagnetic intensity by calibrating it against the VADM data for the Hawaiian lavas. For the last 2 ka I use the Hawaiian lava data [31]. All data have been normalized to the present-day VADM = 8×10^{22} A m^2. (b) Globally stacked record of $^{230}Th_{ex}$-normalized ^{10}Be deposition in deep marine sediments yielding relative variations in ^{10}Be production rate for the last 200 ka [34].

3.2. ^{10}Be production rates

In this study I will use previously estimated variations in ^{10}Be production rate obtained from deep marine sediments. ^{10}Be produced in the atmosphere is quickly attached to aerosols, and then removed via dry and wet precipitation. The atmospheric residence time of ^{10}Be is of the order of a year. The maximum atmospheric deposition of ^{10}Be takes place between 40° and 50° latitude [32]. The residence time of ^{10}Be in the deep oceans appears to be long enough to homogenize the latitudinal fallout pattern. The oceanic processes controlling the transport of particle reactive species to the ocean floor should then determine the ^{10}Be distribution in marine sediments. The record of ^{10}Be flux into deep marine sediment may potentially be compromised from the following climate-related effects: (1) sedimentary focusing and winnowing and (2) recycled ^{10}Be contribution from continental mineral dust. The sedimentary redistribution effects can be eliminated using $^{230}Th_{ex}$ normalization [33,34]. Additional ^{10}Be introduced into ocean basins with detrital material from the continents may bias a purely field intensity-controlled stacked global ^{10}Be flux into marine sediments if its flux is related to climate. Typical ^{10}Be concentration in the continental dust = 5×10^8 atoms/g and marine cores = 3.5×10^9 atoms/g, indicating that large contributions from continental dust would be needed to have a significant impact on the ^{10}Be inventory of the marine core. However, it could be imagined that global hydrography and ocean circulation between glacial and interglacial periods may have been significantly different, impacting not only the latitudinal fallout pattern but also the residence time of ^{10}Be in the deep oceans. This would, of course, introduce systematic errors in the estimated ^{10}Be production rates for glacial and interglacial times. The above effects could be removed by using a stack of several sediment cores from different parts of the world.

I will utilize the recently established globally stacked record of $^{230}Th_{ex}$-normalized ^{10}Be deposition in deep marine sediments that yields relative variations in ^{10}Be production rate over the past 200 ka [34]. Fig. 2b shows the globally stacked production rate of ^{10}Be normalized to present-day (Q/Q_0). It is evident that the ^{10}Be production rate varied by more than a factor of two over the past 200 ka. This record was used by Frank et al. [34] to estimate past variations in geomagnetic field strength assuming a constant solar magnetic activity. Kok [35] has noted that whilst the spectrum of past variations in geomagnetic field strength thus obtained is similar to the independently determined stack of relative paleointensities (= Sint-200 [29]; see below), the record also strongly resembles the $\delta^{18}O$ curve for the same time period. This observation has led him to suggest that climatic influences have not been averaged out in the ^{10}Be compilation. Frank [36], however, has argued that the paleointensity re-

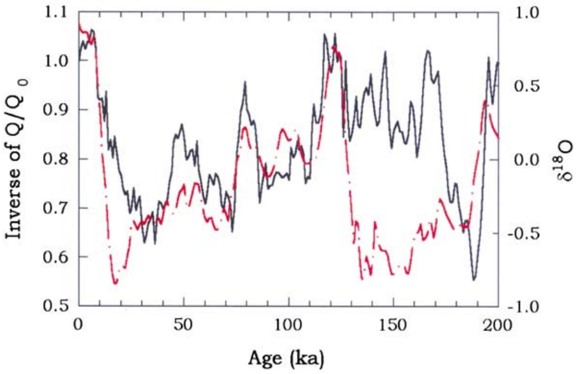

Fig. 3. Plot displaying the inverse of the relative ^{10}Be production rate ($=(Q/Q_0)^{-1}$) plotted against time (solid curve) and compared with δ^{18}O (dotted line) record. In this representation, time-periods with reduced ^{10}Be production rate are shown as peaks. Remarkably, the function $(Q/Q_0)^{-1}$ reproduces gross features of δ^{18}O record.

cords are not significantly affected by climatic factors, although there may still be a 'residual climatic' signal in the record of the production rate of ^{10}Be (M. Frank, personal communication, 2000). This issue is investigated in Fig. 3, where the inverse of the normalized ^{10}Be production rate is plotted against time and compared with the stacked oxygen-isotope record of the oceans [37]. It is interesting that the gross features of the δ^{18}O record can be reproduced by $(Q/Q_0)^{-1}$ suggesting that the estimated ^{10}Be production rate was systematically higher during the glacials and lower during the interglacials. This effect could either be real or due to problems with core selection. Lao et al. [33] have argued that there was a real 30% increase in the ^{10}Be production during the last glacial maximum. In contrast, the observed decrease in the ^{10}Be production rate between 115 and 125 ka may have been due to sampling of cores with uniformly reduced local ^{10}Be rain rates [34]. The latter explanation was offered, however, because Frank et al. [34] observed a significant discrepancy between Sint-200 [29] and their reconstruction of relative paleointensities using ^{10}Be data. An alternative explanation could be that the discrepancy has resulted from variations in solar activity, which was assumed to be constant. However, to the extent that the relative residence times of ^{10}Be and ^{230}Th may have varied between glacial and interglacial times [38], there is still the issue of the extent to which ^{230}Th$_{ex}$ normalization is effective in determining precise relative variations in the ^{10}Be production rate. The rainout rate of ^{10}Be at a given site is ([34] and references therein):

$$\text{Rate} = [^{10}\text{Be}] \times [\text{MassAccumRate}] =$$

$$[^{10}Be] \times \left[\frac{\beta z}{^{230}\text{Th}}\right] \quad (2)$$

Here, β is the production rate of ^{230}Th in the water column, z is the water depth, and [^{10}Be] is the initial concentration of ^{10}Be. A number of cores in the 115–125-ka interval display anomalously high ^{230}Th$_{ex}$ that may have led to lower calculated production rates of ^{10}Be [36]. If true, this observation would constitute the main weakness of the stacked dataset and the results of this study would be biased. Future data would be needed to clarify this issue. An additional source of error in the global stack of ^{10}Be production comes from the assumption that the water depth at the cores sites has remained constant and is equal to the present-day. However, this would lead to an overestimation of ^{10}Be by only $\sim$6% or less during the glacial times when the depth was lower.

Prior to proceeding further, I also need to ensure that the observed variations in the ^{10}Be production rate are not the result of the variations in the sources of energetic particles. Studies of meteorites and lunar samples have indicated that the long-term averaged GCR flux has remained essentially constant within 30% over time periods of 10^4–10^7 yr [39,40]. Solar energetic protons (also called solar cosmic rays, SCR) with energies ≥ 35 MeV can also produce ^{10}Be. Because of the shielding by the geomagnetic field only a small percentage of these particles induce nuclear reactions and that too at the very top of the atmosphere. At present, the SCR contribution to the atmospheric ^{10}Be production is $< 1\%$ [41]. This situation may, however, change during times of extremely low geomagnetic intensities (see below). The ^{10}Be production in the latter scenario may be assessed using the Moon, which has no global magnetic field, as an end-member. Recent studies of lunar silicate samples have demonstrated that SCR flux has provided about 10% of the ^{10}Be production and may have remained constant for the last several hundred thousand years [42]. As the geomagnetic field intensity has not been equal to zero over the past 200 ka and the reaction cross-sections for $^{16}O(p,5pxn)^{10}Be$ are similar to or somewhat higher than those for $^{14}N(p,4pxn)^{10}Be$ at given energies [43], the SCR contribution to ^{10}Be production may be considered an upper limit for terrestrial atmosphere that predominantly contains nitrogen.

A third source of energetic particles is a supernova explosion: propagating shock waves from the explosion may increase the GCR flux at the heliospheric boundary [44]. Due to the short nature of this event, it would be noted as a sharp peak in a time series of ^{10}Be production rate. Indeed, the presence of a ^{10}Be peak in ice cores at ~40 ka has been interpreted to be the result of a supernova [44]. Fig. 2b shows that the relative production rate of ^{10}Be gradually increased from 50 ka, peaked at 36 ka, and then decreased to near present-day values over the next ~25 ka. However, these variations appear to follow concomitant changes in geomagnetic field intensity (Fig. 2a), which is reduced to nearly half its present-day value at ~40 ka. The variations in ^{10}Be production rate therefore appear not to be due to changes in GCR flux.

3.3. Time-tuning of the records

The cores used in both composite records have been dated using globally stacked oxygen-isotope stratigraphy [37] and thus both records are time-tuned to each other. However, in detail there can be some age discrepancy between the two records with uncertainties introduced from various sources, including the sampling rate and sedimentation rate model used and the correlation to the reference value. For example, the ages in between the two tie-points determined by oxygen-isotope stratigraphy were calculated using a linear sedimentation rate for Sint-800 and a ^{230}Th constant flux model for ^{10}Be production. The estimated age uncertainties in the records are, however, of the order of 2–3 ka, and will not introduce large uncertainties in the calculated solar modulation factors.

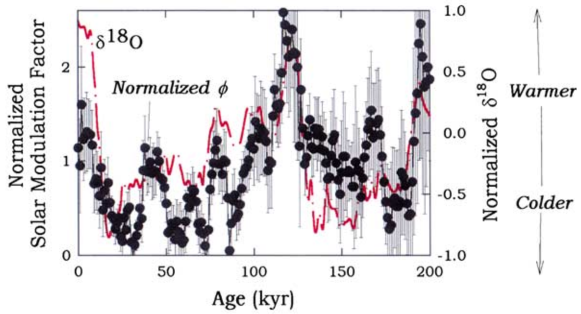

Fig. 4. The normalized solar modulation factor calculated from the records in Fig. 2 using the function in Fig. 1. The plotted formal uncertainties are 1σ standard deviations for each data point. The uncertainties in the y-direction were calculated by propagating errors in the normalized production rate and relative geomagnetic field intensity. The uncertainties in the x-direction were calculated assuming that the age uncertainty in the records is of the order of 2 ka. The resulting uncertainties in the x-direction are smaller than the size of the symbols.

4. Results

The estimated relative variations in the solar modulation factor over the last 200 ka are plotted in Fig. 4. The uncertainties in the modulation factor depend on the estimated uncertainties in ^{10}Be production and in geomagnetic field intensity and were calculated using the Monte Carlo technique. The gross features of the solar modulation over the past 200 ka are: (1) the solar modulation over the last 200 ka has ranged from ~0 to >2, (2) for only one period during the last 200 ka does the ϕ/ϕ_0 significantly exceed 1 (between 111 and 125 ka), and (3) between 25 and 35 ka, and 175 and 190 ka the ϕ/ϕ_0 ratio was close to zero. It is evident that the Sun has experienced at least three periods, each of thousands of years duration, of greatly enhanced and suppressed activity (Fig. 4). In addition, it has also been close to its present level of activity several times during the last 200 ka. The estimated high solar modulation for the time period between 111 and 125 ka is potentially the result of underestimated ^{10}Be production rates during this interval due to anomalously high

$^{230}Th_{ex}$ in the cores (Fig. 2b; see above). In order to estimate the sensitivity of $\phi/\phi0$ calculations for this time interval, I calculated the ^{10}Be production rates for this interval by interpolating those at 110 and 129 ka (see Fig. 2b). This led to on average a 20% increase in the production rates. Using the interpolated values I find that the resulting ϕ/ϕ_0 ratios are not significantly different from 1.0.

Fig. 4 also compares the normalized solar modulation factor with the $\delta^{18}O$ record [37]. Note that the two spectra are much better correlated than the function based solely on ^{10}Be production (Fig. 3). Also, the above correlation results when the correct relationship between ϕ/ϕ_0, M/M_0 and Q/Q_0 (Eq. 1) is utilized and is the reason behind the apparent correlation observed by Kok [35] between $\delta^{18}O$ and M, where the latter was obtained from Q by assuming a constant ϕ. As the ^{18}O record is a proxy of the global ice volume and, in turn, of the Earth's mean surface temperature, the correlation between ϕ/ϕ_0 and $\delta^{18}O$ in Fig. 4 suggests that during the past 200 ka the Earth has experienced a warmer climate whenever the Sun has been magnetically more active. Also, at the height of the last glacial maximum the solar activity was suppressed. These observations are still valid when Q/Q_0 ratios interpolated from those at 110 and 129 ka are used, although the correlation in 4 becomes worse. For the following discussion I will assume that the correlation in Fig. 4 is valid.

5. Discussion

I now address the question of the relationship between proxies for solar surface magnetic activity (ϕ/ϕ_0) and global surface temperature ($\delta^{18}O$). It is clear that a spurious correlation between ϕ/ϕ_0 and $\delta^{18}O$ would result if the estimated M/M_0 and/or Q/Q_0 depended on $\delta^{18}O$ and this issue is central to the arguments for and against the observed relationship. Also, there is the observation of the apparent long-term variability of the solar surface activity, which appears to be cyclical. These issues will be investigated using cross-spectral analysis, although it should be noted that this type of statistical analysis assumes data with Gaussian noise and does not account for systematic shifts from another effect (e.g., anomalously high $^{230}Th_{ex}$ in some cores at a specific time). Finally, the weaknesses of the calculations and future tests to further investigate ϕ/ϕ_0 and $\delta^{18}O$ relationship are discussed.

5.1. Spectral analysis

Spectral analysis of the $\delta^{18}O$ record over the last one million years has indicated the existence of cycles with periods of 23 ka, 41 ka and 100 ka [45]. The questions that we need to address are: (1) whether the ϕ/ϕ_0, M/M_0 and Q/Q_0 display spectra with power at frequencies resembling those obtained from $\delta^{18}O$ record, and (2) to what extent do the ϕ/ϕ_0, M/M_0 and Q/Q_0 spectra cross-correlate with the $\delta^{18}O$ spectrum. Fig. 5a plots the time-integral power spectral densities (PSD) obtained for the data against frequency and shows that ϕ/ϕ_0 and M/M_0 have PSD concentrations at a wavenumber of 0.01 (= 100-ka cycle), identical to that for the $\delta^{18}O$ record, which for the purpose of this analysis was truncated at 200 ka. On the other hand, the Q/Q_0 does not appear to have PSD concentrations at any wavenumber.

Does the above analysis indicate that the estimated geomagnetic field intensity depends upon $\delta^{18}O$? I investigate this issue using cross-analysis of spectral power that provides a more quantitative assessment to determine the degree of resemblance of two data sets. The source code for this calculation called CROSS uses a Fourier multitaper estimation based on sine weight functions [46,47]. The calculation gives squared coherence and phasing between two spectra of interest. The squared coherence γ^2 of two uncorrelated Gauss–Laplace distributed time series are expected to fall below a calculated zero coherence level 95% of the time. Phasing of the spectra can be used in conjunction with γ^2 as an additional measure to evaluate the degree of resemblance [47]. Fig. 5b,c shows the squared coherence and phase, respectively, as a function of frequency for ϕ/ϕ_0 and $\delta^{18}O$, M/M_0 and $\delta^{18}O$, and Q/Q_0 and $\delta^{18}O$. Significant cross-spectral coherence between ϕ/ϕ_0 and $\delta^{18}O$ at wavenumbers ≤ 0.05 is evident in Fig. 5b (see also Fig. 4). At wavenumbers ≤ 0.02 the data are also in phase. In contrast,

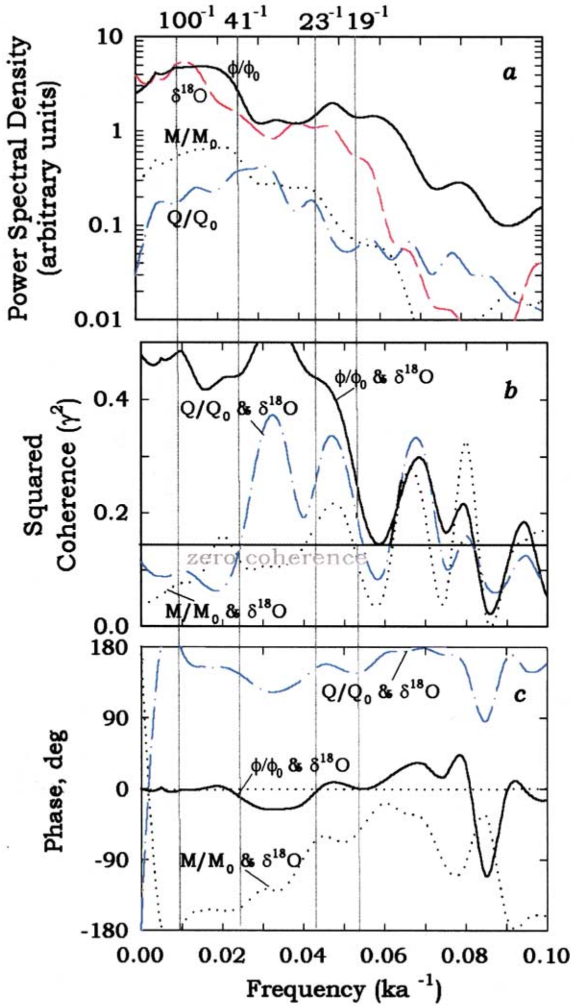

Fig. 5. (a) Time-integral PSD plotted against frequency. Note that ϕ/ϕ_0, M/M_0 and as expected $\delta^{18}O$ have PSD concentrations at a wave number of 0.01 (=100-ka cycle). The Q/Q_0 does not have PSD concentrations at any wavenumber. The PSD concentrations were estimated using AutoSignal from SPSS Science as well as CROSS. (b) Squared coherences are significant for ϕ/ϕ_0 and $\delta^{18}O$ and Q/Q_0 and $\delta^{18}O$ at some frequencies but not for M/M_0 and $\delta^{18}O$. (c) Phase of squared coherences of panel b. Only ϕ/ϕ_0 and $\delta^{18}O$ at wavenumbers >0.02 are in phase. These observations indicate that the 100-ka ice age cycle and solar activity are strongly related.

the M/M_0 and $\delta^{18}O$ cross-spectrum does not display any coherence. The Q/Q_0 and $\delta^{18}O$ cross-spectrum, while coherent between wavenumbers 0.024 and 0.05, is not in phase. Taken together, the above results suggest that the long-term solar activity and Earth's surface temperature are directly related. Furthermore, the spectral analysis suggests that the 100-ka cyclicity observed in the $\delta^{18}O$ record may be related to solar modulation. The latter observation is intriguing as it could provide yet another astronomical driver of the notorious 100-ka cycle of the ice ages.

5.2. Sun and the 100-ka cycle

The ice ages, according to the Milankovitch theory, are the consequence of secular variations in solar insolation caused by changes in the Earth's orbital parameters [45,48,49]. The marine $\delta^{18}O$ record has shown that, while the Earth has been cooling for the last 40 Ma, the ice ages marked by relatively cold (glacial) and warm (interglacial) periods began $\sim$2.5 Ma ago. With the exception of the last one million years, the glacial–interglacial cycles are dominated by periodicities corresponding to the predicted cycles of orbital obliquity (41-ka cycle) and precession of the Earth's orbit (23-ka cycle). A 100-ka oscillation is the most dominant during the last one million years [50] and corresponds rather closely to the predicted cycles of orbital eccentricity (95 ka and 125 ka). However, the eccentricity variations are rather insignificant and the predicted solar insolation changes too small ($<0.2\%$) to induce climate changes by direct forcing [51]. As the Milankovitch theory implicitly assumes the Sun to be a source of constant radiation on a million-year timescale, non-linear models invoking ice-sheet dynamics have been propounded to explain the existence of the 100-ka cycles [51,52]. This has led to another problem: a 400-ka cycle predicted by the eccentricity variations is absent from the $\delta^{18}O$ record [51,53,54] but strengthened by the non-linear ice models [55].

The 100-ka problem is discussed in detail by Muller and MacDonald [55–58], who argued that by looking at the narrowness of the 100-ka spectral peak it could only be generated through astronomical forces and not through internal oscillations, which would tend to broaden it. They also discovered that changes in the inclination of the Earth's orbit follow a 100-ka cycle and argued that such variations would engender periodic cosmic dust accretion on Earth, which may lead to climatic changes on 100-ka timescales [55–58]. This astronomical hypothesis, however, suffers from the absence of any concrete physical mechanism through which significant changes in climate result from accretion of cosmic dust. So, in contrast to the observed 23-ka and 41-ka cycles in marine records, which can be explained by solar insolation cycles, an understanding of the 100-ka cycle remains elusive. A recent study suggests that the 100-ka cycle does not arise from ice sheet dynamics but is generated in response to changes in atmospheric carbon dioxide concentration [59]. Yet the general argument that the 100-ka cycle must be astronomically driven [55,57] should be valid. Figs. 4 and 5 show that the $\delta^{18}O$ record and solar modulation are coherent and in phase on a 100-ka timescale. The simplest explanation of this observation is that variations in solar surface magnetic activity cause changes in the Earth's climate on a 100-ka timescale.

As mentioned above, there are strong correlations between solar surface magnetic activity and climate at different timescales, which range from days through centuries. Whereas these observations have pointed to a causal relationship between solar activity and climate change, the details of physical mechanism(s) still need to be worked out (see e.g., [60]). It has been generally believed that the variations in solar magnetic activity lead to changes in total or ultraviolet irradiance of the Sun through the disc passage and evolution of sunspots and faculae [3–5,61], which, in turn, affects climate. Another posited mechanism through which solar activity could directly affect climate is via modulation of GCRs, which influences cloud formation by inducing changes in the tropospheric ion production [8–10,62,63]. If the changes in cosmic ray flux cause cloud cover variations, one would expect an inverse relationship between solar modulation and surface temperature, assuming that the proportion of low and high clouds remains constant. This is consistent with the observation in Fig. 4, although variations in irradiance could also affect climate by e.g., affecting the ozone cover [7]. However, it is not apparent why the solar activity should vary on a 100-ka timescale.

Observations over the last few centuries have shown the solar activity to vary with an 11-yr periodicity of sunspots (Schwabe cycle), a 22-yr oscillation in solar magnetic polarity (Hale cycle) and an about 90-yr period of a sequence of low sunspot numbers (Gleissberg cycle). Additionally, the cosmogenic nuclei proxies indicate solar oscillations of 1/420 yr^{-1} [20] and 1/1500 yr^{-1} [21]. If the presence of a 100-ka solar activity cycle could be further substantiated, it would help elucidate processes occurring deep within the Sun's interior. Observations of Sun-like stars have shown them to be a much more magnetically variable [6,64] and thus it is conceivable that in comparison to its present state, the Sun could have been more or less magnetically active in the past. However, the current models of solar magnetohydrodynamics are not sufficiently developed to predict long-term solar activity variations (e.g., [65–67]).

In summary, it is evident that while there are strong correlations between solar activity and climate at different timescales more work is needed towards finding mechanisms that change the solar activity in the first place and that explain the physical link between the solar magnetism and climate. Nevertheless, if the results of this study can be further substantiated, a causal connection between solar surface magnetic activity and 100-ka cycle would be consistent with other short-term observations mentioned above.

5.3. Caveats and further tests

5.3.1. Data length and uncertainty

First of all, it is important to recognize that the calculations presented in this study encompass only two cycles of the postulated 100-ka solar activity variations. While it is possible to extract the 100-ka cycle from a 200-ka-long record (as shown above using the $\delta^{18}O$ record truncated at 200 ka), one needs to extend this calculation to >1 Ma in order to ratify the claims of this study. It is, however, easier said than done: a reliable ^{10}Be production record requiring ^{230}Th normalization is not possible beyond 250 ka. This issue is discussed in Section 5.3.2. Also, the geomagnetic field intensity is not well constrained prior to 800 ka. While it may be difficult to obtain a continuous record of geomagnetic field variations, well-dated submarine basalt glasses could provide discrete VADMs [68,69].

The calculations presented here make use of data obtained by stacking a series of data points. In doing so the authors developed certain subjective criteria to combine selected data sets and to reject others. Guyodo and Valet [30] used 33 different cores to estimate the M/M_0 for the last 800 ka. They describe in detail the manner in which they combine data in an initial study where they used 17 different cores to estimate the M/M_0 for the last 200 ka [29]. In addition to utilizing established selection criteria, these authors used a bootstrap method to remove one of the cores from the data. This led to a considerable reduction in the estimated uncertainties.

The ^{10}Be production rate at each time step was calculated in the following manner [34,70]: the $^{230}Th_{ex}$-normalized deposition rate was calculated for each sample and interpolated to a 1-ka interval knowing the $\delta^{18}O$ or ^{14}C chronology and in case of continuous core samples high resolution dating using a $^{230}Th_{ex}$ constant flux model. In order to reduce enrichments/depletions due to local effects (e.g., boundary scavenging), the estimated ^{10}Be deposition rates in each core were normalized to their average values. Finally, the data for each time step were globally averaged. The number of records used at each time step is variable with 10–31 records between 0 ka and 144 ka and with four to nine records between 145 ka and 200 ka. A large number of cores used by Frank et al. [34] are clustered in the South Atlantic. Additional data from other oceans and from different latitudes need be combined to obtain a more global coverage.

While both ^{10}Be production rate and geomagnetic field intensity records were carefully prepared to minimize introducing a bias to the data, it is possible that selection criteria may have led to a reduction in data scatter and, consequently, a smaller apparent uncertainty in the calculated solar modulation factor. A major problem, as discussed above, is that certain cores used to determine ^{10}Be production rate may have anomalously high $^{230}Th_{ex}$. If true, the observed variations in the solar modulation factor would be swamped by noise. Future tests with better datasets are therefore essential to investigate the claims made in this study.

5.3.2. Tests

The most important test of the hypothesis presented in this study would be to re-determine ϕ using other datasets and to search for periodicities. It would be discarded if the predicted correlation between ϕ and climate is not seen. In view of the potential problems with the ^{10}Be production record used in this study, a simpler and robust test is to use well-characterized Fe–Mn crusts, which display constant $^{10}Be/^{9}Be$ ratios [71] and whose growth rate have been estimated using $^{230}Th_{ex}$ dating. High resolution sampling of such crusts (resolution = 10–20 ka) and determination of ^{10}Be and ^{9}Be in resulting aliquots would provide data that could be used in conjunction with Guyodo and Valet's Sint-800 [30] to estimate ϕ/ϕ_0. This is a technically challenging problem given that the number of atoms to be measured would be rather small.

In order to minimize errors introduced in the calculations due to the stacked nature of Q and M records, it may be useful if normalized ϕ were obtained on individual cores and then globally averaged. This is a challenging task and would entail selecting those cores where Q and M as well as high resolution $\delta^{18}O$ data could be reliably obtained. Useful sites around the globe would be those at low latitudes, away from the continents in relatively deep water, and displaying a relatively constant sedimentation rate. Southon et al. [72] found that ^{10}Be is 10 times more enriched in clays than in carbonates. As dissolution of carbonates could be problematic, it would be important to concentrate on cores with a high clay to carbonate ratio. In order to minimize the effects due to sediment focusing and winnowing, normalization with $^{230}Th_{ex}$ could be used for samples less than 250 ka old [33,34,70] on cores that do not display anomalously high $^{230}Th_{ex}$ [36,38]. For samples older that 250 ka one could use another normalizing element such as ^{3}He in interplanetary dust particles [73–75], although this method does have its own set of problems [76].

Another test would be to compare activities of cosmogenic nuclides in well-dated surfaces. The best surfaces for such purpose are coral terraces, which have been dated quite precisely using U–Th systematics (e.g., [77,78]). The spallation target in corals is ^{40}Ca and its interaction with neutrons and negative muons produces ^{36}Cl ($t_{1/2} = 300$ ka) (e.g., [79]). The relative production rates of ^{36}Cl in corals from a given study area would reflect past changes in solar modulation of GCR. As with any exposed surface, two variables that would potentially control the measured ^{36}Cl concentration and, therefore, impact the estimated production rate in coral terraces are their erosion and burial under debris. Independent estimates of the extent to which these processes may have operated on these surfaces would be needed a priori to assess the variations in ^{36}Cl production rate.

6. Conclusions

Using the established variations in geomagnetic field intensity and ^{10}Be production rates, I have determined the variations in solar modulation of galactic cosmic rays over the past 200 ka. The variations in solar modulation indicate that the Sun displays periods of enhanced and suppressed magnetic activity that are of several thousand years in duration. Spectral and cross-spectral analyses indicate that the solar activity has a 100-ka cycle in phase with the $\delta^{18}O$ record of glacial–interglacial cycles. The long-term solar activity and Earth's surface temperature appear to be directly related. The variations in solar activity may control the 100-ka glacial–interglacial cycles providing a more tangible astronomical forcing than the estimated changes in solar insolation or cosmic dust accretion rates. Further tests using high fidelity datasets, which give time-tuned geomagnetic field intensity and cosmogenic radionuclide production rates, would be needed to substantiate this hypothesis.

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