

# Variations in the production of $^{10}\text{Be}$ due to the 11 year modulation of the cosmic radiation, and variations in the vector geomagnetic dipole.

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**Abstract.** The 11 year variation in the production and precipitation of  $^{10}\text{Be}$  at Dye 3 in Southern Greenland is investigated in detail, and shows that the  $^{10}\text{Be}$  was produced at geomagnetic cutoffs  $< 1\text{GV}$ . Using this result, a mathematical model was developed that shows that the changes in direction, and intensity of the geomagnetic dipole since 1000AD have modulated the production of  $^{10}\text{Be}$  by up to 4%. Analysis of the  $^{10}\text{Be}$  data shows that the 11 year variation is well described by the force field modulation function, after allowance for century scale changes in the cosmic ray spectrum. Further, the changes in modulation function are shown to be a well defined function of sun spot number throughout the interval 1784-1976. In addition, it is shown that the well known 22 year variation due to drift effects in the heliomagnetic field can be identified in the  $^{10}\text{Be}$  data. This shows that the 22 year oscillation in the sun's general field did not suffer a phase slip between the 19<sup>th</sup> and 20<sup>th</sup> century Gleissberg cycles. Overall, these results indicate that the  $^{10}\text{Be}$  data will provide good estimates of sunspot number, and phase of the heliomagnetic field, far into the past.

## 1 Introduction

Careful pioneering work has shown that the cosmogenic isotopes, principally  $^{10}\text{Be}$ ,  $^{14}\text{C}$ , and  $^{36}\text{Cl}$ , as recorded in biological material, ice cores, and recent geological sediments, exhibit time variations that were synchronous with the major changes in solar activity over the past four centuries. Peters, Lal, Stuiver, Damon, Beer, Raisbeck, Yiou, Castagnoli, and many others have contributed to this understanding. It has been shown that the only tenable explanation of these variations is that they are due to modulation of the cosmic radiation by the physical processes associated with the solar wind.

This purpose of this and another paper herein (McCracken and McDonald, 2001) is to reverse this process, and use the cosmogenic data to extend our knowledge of the modulation process itself, and set limits on the properties of the local interstellar cosmic ray spectrum; that is, on the cosmic ray spectrum outside the heliosphere.

## 2 Data Analysis

This paper uses the annual concentrations of  $^{10}\text{Be}$  obtained at Dye 3, in southern Greenland ( $65^{\circ}\text{N}$ ), as given by Beer et al (1990). All  $^{10}\text{Be}$  data have been passed through a time series filter with weights of 1,2,1 to reduce high frequency noise prior to analysis. The standard deviations used for the  $^{10}\text{Be}$  data throughout this paper are derived from an analysis summarized in Sect. 7. The observed concentrations of  $^{10}\text{Be}$  are influenced by four major factors; the production rate; the redistribution of the  $^{10}\text{Be}$  in the atmosphere; the  $^{10}\text{Be}$  precipitation; and variable dilution by time changes in the annual snowfall. Of these factors, the first two are considered here, and the others elsewhere in this conference (McCracken and McDonald, 2001).

This paper makes frequent use of the concept of the modulation function  $\phi(t)$  as defined by Gleeson and Axford (1968), and since used successfully to interpret the long term variations of the cosmic ray spectrum over the energy range 0.05-20 GeV/nucleon.  $\phi(t)$  is defined as an integral that incorporates the radially dependent solar wind speed and cosmic ray diffusion coefficients, and as such represents a number of the most important parameters that describe the effects of solar activity on the heliosphere.

The "superposed epoch" method of analysis is used here to establish the amplitude and temporal characteristics of the 11 year variations since 1784. Briefly, if  $C(N, t_i)$  is the  $^{10}\text{Be}$  concentration for the  $i^{\text{th}}$  year of the  $N^{\text{th}}$  sunspot (Schwabe) cycle, then the average  $\Gamma(t_i)$  is computed over a specified set of sunspot cycles (ie, values of  $N$ ) for each  $t_i$ . A linear trend correction is applied, and the resulting dependence on time (ie phase) within the 11 year variation is expressed as a percentage relative to the maximum value of  $\Gamma(t_i)$  within the cycle. The first year of each cycle (ie,  $t_i$ ) is defined as the year after the year of lowest annual sunspot number at the start of the  $N^{\text{th}}$  cycle (to allow for the 1 year residence time of the  $^{10}\text{Be}$  before precipitation).

Figure 1 presents the 11 year variations in  $^{10}\text{Be}$  concentration for a number of sets of solar cycles between 1784 and 1972 (Schwabe cycles 4 to 20). The 11 year variations are clearly defined in each, and there are clear differences that are analyzed below.

### 3 The Source of the $^{10}\text{Be}$ Observed in the Polar Cap

The calculations of Masarik and Beer (1999) indicate that the rate of production of  $^{10}\text{Be}$  in the earth's atmosphere is a strong function of latitude; the production rate at high latitudes being as high as 2.7 times the global average. It is therefore necessary to know the extent of the source region of the  $^{10}\text{Be}$  recorded in polar ice in order to reach quantitative conclusions regarding the changes in cosmic ray spectrum as recorded by the  $^{10}\text{Be}$ .

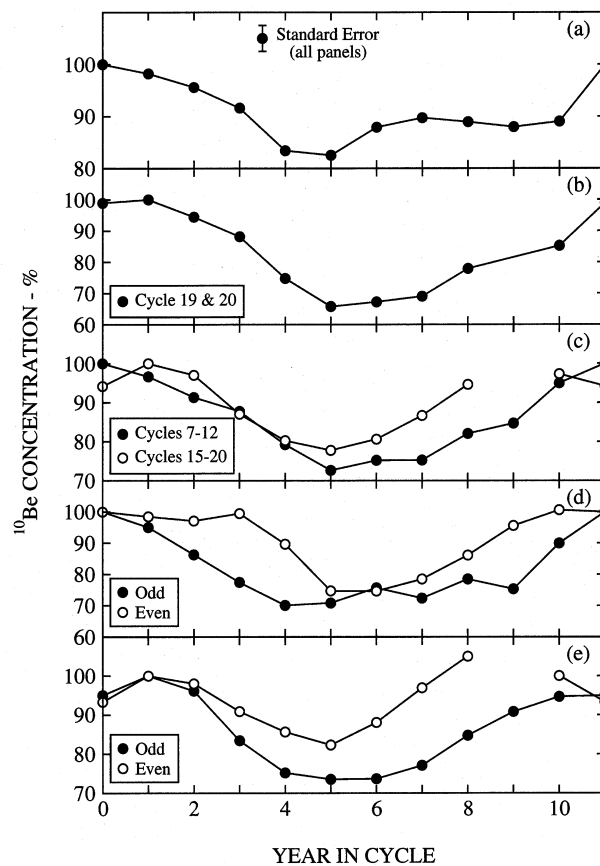
Steig et al (1996) and Bard et al (1997) have concluded that  $\geq 70\%$  of the  $^{10}\text{Be}$  precipitated at Taylor Dome ( $78^\circ\text{S}$ ), and at the South Pole, respectively, has been produced at high latitudes. By way of contrast, Beer et al (1990) have estimated that the data used herein from Dye 3 ( $65^\circ\text{N}$ ) represents the global average rate of production of  $^{10}\text{Be}$ . Masarik and Beer (1999) have used their comprehensive calculations of the production rates of nucleons, and the Deep River neutron monitor data, to compute the time dependence of the modulation parameter,  $\phi$ , over the period 1954-1990. Averaging their results over the two Schwabe cycles 19 and 20 (1954-1976),  $\phi$  varied from 440 to 1005 MeV over the 11 year variation in cosmic ray intensity. Using the production rate curves of Masarik and Beer (1999), this change in  $\phi$  predicts a 34.4% decrease in  $^{10}\text{Be}$  production at cutoffs  $< 1\text{GV}$ ; and a 21.6% decrease in the global average production rate.

The 11 year variation in the Dye 3 data, averaged over Schwabe cycles 19 and 20, has an amplitude of 34.8% (See Fig. 1b). This is statistically indistinguishable from the  $< 1\text{GV}$  prediction (34.4%) and greatly different from the prediction for the global average (above). Clearly, the  $^{10}\text{Be}$  precipitated at Dye 3 was primarily produced at cutoffs  $< 1\text{GV}$ , a result very similar to those of Steig et al (1996) and Bard et al (1997). This result is used here and in the companion paper to compute the cosmic ray spectral changes associated with the observed dependence of  $^{10}\text{Be}$  concentration on time.

### 4 Characteristics of the 11 year cycle; 1784-1976.

Figure 1a-e presents the 11 year variations averaged over a number of different groupings of Schwabe cycles. Figure 1a, corresponding to cycles of low solar activity, indicates a relatively low amplitude 11 year variation. Figure 1c presents averages over the 19<sup>th</sup> Century, and the 20<sup>th</sup> century Gleissberg cycles of solar activity, and they exhibit a striking anti correlation between the amplitude of the 11 year variation and solar activity. Thus the amplitude of the  $^{10}\text{Be}$  variation for the 19<sup>th</sup> Century Gleissberg cycle was larger than that of the 20<sup>th</sup> Century, while the average peak sun spot numbers were 85.1 and 121.0, respectively.

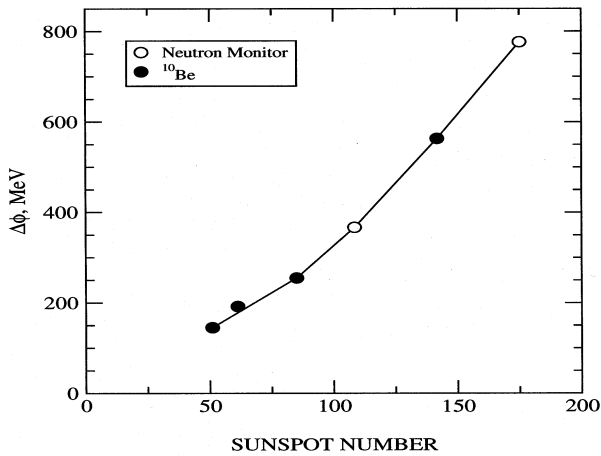
This anti correlation can be understood as follows. McCracken and McDonald (2001) shows that there was a 30% decrease in  $^{10}\text{Be}$  concentration between the two Gleisberg cycles, which is consistent with the modulation function  $\phi(t)$  being in the vicinity of zero MeV during the



**Fig. 1.** Superposed epoch analyses of the 11 year variations in the  $^{10}\text{Be}$  data for the following Schwabe cycles (a) 5,6,12,14; (b) 19,20; (c) as shown; (d) 7-12 and (e) 15-20.

sunspot minima of the Schwabe cycles in the 19<sup>th</sup> Century. As such, the intensity of cosmic radiation in the energy range 0.1-1 GeV/nucleon would have been between 30 and 3 times higher than in the vicinity of 1950. Clearly then, a given change in  $\phi(t)$  will have resulted in a greater contribution to  $^{10}\text{Be}$  production by the lower energies in the 19<sup>th</sup> century than in the period after 1950. As an example; using the  $^{10}\text{Be}$  yield curves of Masarik and Beer (1999), and assuming a change of  $\phi(t)$  of 100MeV, the decrease in the high latitude  $^{10}\text{Be}$  production rate in the 19<sup>th</sup> Century would have been 11.1%, and 7.1% after 1950. That is, the amplitude of the 11 year modulation of the  $^{10}\text{Be}$  production rate will have been reduced by a factor of 0.64 (7.1/11.1) as a direct consequence of the preferential reduction of the cosmic radiation at lower energies between the 19<sup>th</sup> and 20<sup>th</sup> centuries. Application of this factor to the data in Fig 1c yields an 11 year variation of 17.3% for the 19<sup>th</sup> century; eliminating the anti correlation; and indicating that there was a monotonic increasing dependence of the amplitude of the 11 year variation upon solar activity.

Figure 2 analyses the long term changes in the 11 year variation in another manner. Using the Masarik and Beer



**Fig. 2.** The observed dependence of the changes in modulation function upon peak sunspot number. The three points nearest the origin are from the nineteenth century.

yield functions, the changes in modulation function  $\Delta\phi(t)$  that yield the observed 11 year variations in neutron monitor and  $^{10}\text{Be}$  data have been calculated. Figure 2 shows that there is an extremely good relationship between  $\Delta\phi(t)$  and the mean peak sunspot number throughout the whole interval 1800-1976. The correlation is worse if the long term change in the cosmic ray spectrum is ignored.

The relationship presented in Fig 2 will allow annual or biannual  $^{10}\text{Be}$  data from periods prior to 1600 to be used to estimate the maximum sunspot number for Schwabe cycles in the past. Thus if  $\gamma$  is the slope of the line in Fig. 2, and  $\phi_{max}$  and  $\phi_{min}$  are the values of the modulation function corresponding to the maximum and minimum values of the 11 year variation of  $^{10}\text{Be}$ ; then the peak annual sunspot number for that cycle is approximated by  $(\phi_{max} - \phi_{min})/\gamma$ .

### 5 The sign of $qa$ for the Schwabe cycles in the 19<sup>th</sup> century.

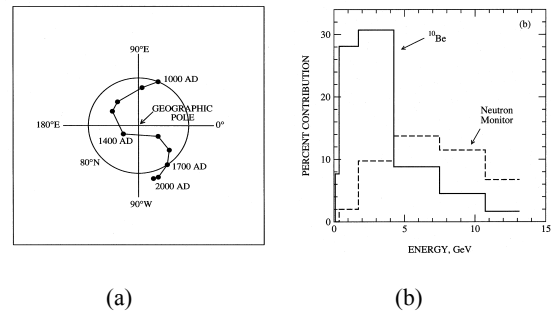
The neutron monitor data observed since 1951 and more recent satellite data show a large and characteristic difference between successive 11 year variations at all energies  $<20\text{GeV}$  (McDonald, 1998). Thus, in the period since 1951, the odd numbered cycles (17,19) have exhibited a relatively broad 11 year variation, while the even numbered cycles (18, 20) have had a shorter lived decrease, returning to the sunspot minimum value several years prior to sunspot minimum. This difference in behavior is the consequence of the particle drifts which reverse their direction of motion during the 22 year heliomagnetic cycle. Thus in the period since 1900, the even cycles have corresponded to an outward directed magnetic field in the sun's northern hemisphere ( $qa > 0$ ). The odd cycles, with an inward field, correspond to  $qa < 0$ . The difference in character of the 11 year variations is very marked, and calculations based upon the cosmic ray effects observed

since 1951 indicated that they should be discernible in the  $^{10}\text{Be}$  data.

Figures 1d and e display the 11 year cycles for the odd and even numbered Schwabe cycles in the 19<sup>th</sup> century and 20<sup>th</sup> century Gleissberg cycles. Note that the odd/ even characteristic is the same for both Gleissberg cycles. This shows that the phase of the 22 year periodicity in the solar field did not change between the two Gleissberg cycles.

### 6 The effects of changes in the vector geomagnetic dipole upon $^{10}\text{Be}$ production.

In view of the conclusion in Sect.2 that the  $^{10}\text{Be}$  in polar ice cores is primarily due to the production of  $^{10}\text{Be}$  at high geomagnetic latitudes, it is clear that the production region will move as a consequence of "polar wander". As Fig 3a shows, the earth's geomagnetic pole has moved some  $21^\circ$  since 1000AD, and the dipole strength has decreased by 25% over the same period (McElhinny and McFadden, 2000). The combined effect on the geomagnetic cut off is quite considerable; for example, the location (48N, 285E) in the north American continent with a 1 GV vertical Stoemer cutoff in 2000AD would have had a cutoff of 5.2GV in 1000AD due to polar wander, and 7.1 GV when the change in dipole strength is included. This time dependence of the cutoff will have an impact upon the cosmic ray intensity in the atmosphere, which could be of consequence in using  $^{10}\text{Be}$  data to study cosmic ray phenomena.

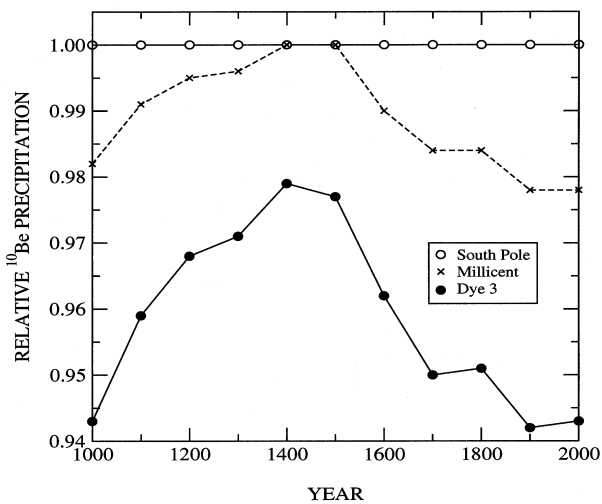


**Fig. 3.** (a) The motion of the North geomagnetic pole, 1000-2000AD. (b) The energy response of polar  $^{10}\text{Be}$ , and a high latitude neutron monitor, during the solar cycle minimum of 1965.

A mathematical model was developed to compute the  $^{10}\text{Be}$  precipitation rate at various polar locations as a function of time. The zonal (ie circumpolar) motion of the atmosphere means that the  $^{10}\text{Be}$  precipitated in Greenland, say, has been produced at other longitudes and then deposited days, weeks and months later in Greenland. The model includes this major atmospheric effect (which is a function of the residence time of the  $^{10}\text{Be}$  in the stratosphere and troposphere); it computes the vertical Stoemer cutoff at all latitudes and longitudes that contribute to the Greenland precipitation; it uses the Masarik and Beer yield curves to estimate the  $^{10}\text{Be}$  production throughout the production region; and then integrates over all contributions. The fact

that the  $^{10}\text{Be}$  response is integrated over all longitudes means that the non dipolar terms in the geomagnetic field only have a second order effect, and this was not included in the model reported here.

Figure 4 presents the time variation in  $^{10}\text{Be}$  precipitation for three locations that have been important sources of  $^{10}\text{Be}$  data, for the interval 1000-2000AD. As is to be expected, the effects of polar wander increase with decreasing latitude. Using the estimate of random error from Sect. 7, the standard deviation of decade averages will be about 2.5 %. Thus the 4% variation computed for Dye 3 is only marginally significant in decadal averages. Nevertheless, for long term studies such as in the companion paper, it is important that the amplitude of this effect is known to allow compensation, or to eliminate it as a potential cause of an observed effect.



**Fig. 4.** The calculated changes in  $^{10}\text{Be}$  precipitated to three polar locations due the long term changes of the geomagnetic dipole.

### 7 Analytical characteristics of the $^{10}\text{Be}$ data.

The 11 year variability examined here, and the long term variation examined elsewhere (McCracken and McDonald, 2001), totally dominate the variance of the raw  $^{10}\text{Be}$  data. A statistical analysis shows that the random ("noise") component is  $.035 \times 10^4$  atoms/g in the Dye 3 data in 1954-76. This is at the lower limit of the noise estimates of Beer et al (1990), and adds substantially to the significance of the results based on their data.

The data in Masarik and Beer (1999) were used to compute the  $^{10}\text{Be}$  contribution as a function of energy, as displayed in Fig.3b. The energy dependence of a sea level neutron monitor is shown also (data from Carmichael and Berkovitch, 1969). Note that the  $^{10}\text{Be}$  response extends to much lower energies than does the neutron monitor, still being significant at 300MeV/nucleon. Computations show that for 1965 the mean energy of response of the  $^{10}\text{Be}$  data was 2.6GeV/n, compared to >6.2GeV/n for the neutron

monitor. For the 19th century, the mean  $^{10}\text{Be}$  response was 1.95GeV/n as a result of the higher fluxes of low energy particles for  $\phi=0$  (McCracken and McDonald, 2001).

For the mean 11year variation for Schwabe cycles 19 and 20 (Fig.1b), the ratio ( $^{10}\text{Be}$  change/Climax neutron change) =  $(34.8/15.0) = 2.3$ . This confirms that the  $^{10}\text{Be}$  data sample considerably lower energies than does a neutron monitor, thereby bridging the gap to the higher energy windows on many satellite cosmic ray instruments.

### 8 Conclusions

This paper has demonstrated that the  $^{10}\text{Be}$  preserved in polar ice cores provides a sensitive record of the historical cosmic ray variations in the vicinity of 2 GeV. Further, it has shown that the  $^{10}\text{Be}$  data provide a quantitative means to estimate sunspot numbers prior to 1610; and to determine the phase of the 22 cycle of the heliomagnetic field prior to 1895. As such, the  $^{10}\text{Be}$  cosmic ray data can provide an important key to an improved understanding of the magnetic properties of the sun far into the past.

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