The Long-Term Variability of the Cosmic Radiation Intensity at Earth as Recorded by the Cosmogenic Nuclides

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Introduction

Long-term instrumental measurements of the 1-100GeV/nucleon cosmic radiation intensity commenced in the 1930s using ionization chambers[1], and in 1951 using neutron monitors[2]. Together, they showed that the cosmic-ray intensity at Earth varies in response to short-term (<1 year) and the 11-year changes in solar activity. B. Peters[3] predicted in 1955 that the production of the cosmogenic isotopes in the Earth's atmosphere, and their subsequent storage in terrestrial archives, had provided a record of the cosmic-ray intensity prior to the commencement of instrumental measurements. The most abundant cosmogenic nuclides, ^{10}Be and ^{14}C, with half-lives of 1.5×10^9 and 5730 years, respectively, are well-suited to this purpose, and by the mid-1990s there were comprehensive archives of both nuclides extending over the past 50,000 years (^{14}C in tree rings and marine and lake sediments) and several over 100,000 years (^{10}Be in polar ice cores and sediments).

During the ISSI workshop "Cosmic Rays and Earth"[4] on the worldwide neutron monitor network, in 1999, it was emphasised that the cosmogenic radionuclides constitute a natural form of neutron monitor[5]. This and other work[6] was instrumental in establishing an analytical base that now allows the ^{10}Be and ^{14}C data to be used to investigate the temporal variability of the cosmic radiation in the past. Other workers[7,8] provided further insight into the geomagnetic and other effects in the cosmogenic data. In particular, it was shown that the ^{10}Be data provide a measurement of cosmic rays of lower energy than in the case of the neutron monitor (^{10}Be peak response ≅ 1.8 GeV/nucleon, compared to 6 GeV/nucleon for a high-latitude, sea-level neutron monitor).

Based on these several advances, the cosmogenic data are now used to investigate the levels of solar activity, the state of the heliosphere, and the manner in which the interplanetary magnetic field has changed over the past millenium[9-11], and they are being used as a proxy for the interplanetary field and in climate studies by others[12]. Recognising this widespread interest, a workshop "^{10}Be, ^{14}C, the Sun, and the Heliosphere" was held at ISSI in 2003 and brought together several key scientific communities (specialists in cosmogenic radionuclides, cosmic-ray modulation, cosmic-ray and solar theory). This workshop further stimulated investigations into the temporal variability of the cosmic-ray intensity at Earth in the pre-instrumental era, as outlined in the following.

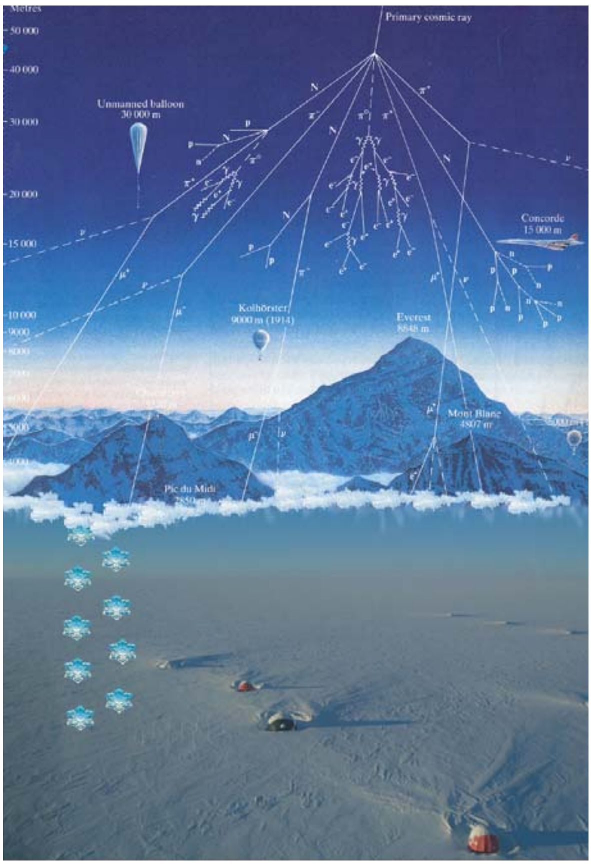

Figure 1. Illustrating the nucleonic cascade and atmospheric processes that generate the cosmogenic nuclides observed on Earth. The "primary" cosmic ray that has reached Earth from the Galaxy interacts with atmospheric nuclei to produce nucleonic and electromagnetic cascades. The neutrons and protons then interact with other atmospheric nuclei to yield the cosmogenic nuclides ^{10}Be (half life 1.51×10^6 years); ^{14}C (5730 years) and others. The ^{10}Be is precipitated to Earth with snow in the polar regions, and is then compacted into ice, which is then sampled by a drilling system. The ^{14}C remains in the atmosphere as CO_2 and participates in the biological carbon cycle.

The Cosmogenic Nuclides as Cosmic-Ray Detectors

The underlying principle is the same for both the instrumental, and cosmogenic methods of recording the cosmic-ray intensity. In the instrumental cosmic-ray detectors (e.g. ionization chamber, neutron monitor, etc.), the secondary cosmic-ray mesons or nucleons produce electronic responses in the detector, and these are summed to yield the total cosmic-ray flux over an appropriate period of time. In the case of the cosmogenic nuclides[5], the cosmic rays undergo nuclear interactions with the nuclei of the gases in the Earth's atmosphere, yielding radionuclides such as ^{10}Be and ^{14}C that are not otherwise present on Earth (Fig. 1). Since no on-line recording of the interaction is possible (as in an instrumental detector), a memory is needed which reliably stores this information and which can be read out centuries or millennia later. This recording function is provided by the deposition of the cosmogenic ^{10}Be in snow in the polar caps and in ocean sediments, and by the uptake of cosmogenic ^{14}C in biological materials such as tree rings. In principle, the concentration of the cosmogenic nuclide then yields the cosmic-ray intensity, at the time in the past determined by an independent means. In the case of ^{10}Be in ice, the time scale is established by several means (e.g. the annual variations in the isotope ^{18}O and dust trapped in the ice; volcanic time markers, and ice flow models); in the case of ^{14}C sequestered in trees, by counting the annual rings.

Figure 2. Illustrating the first stages of the measurement of ^{10}Be concentration in ice. A small drilling system used to recover a short (~300 m) core in Greenland is shown. The ice core was then protected against contamination and, following sample preparation, analysed using an accelerometer mass spectrometer.

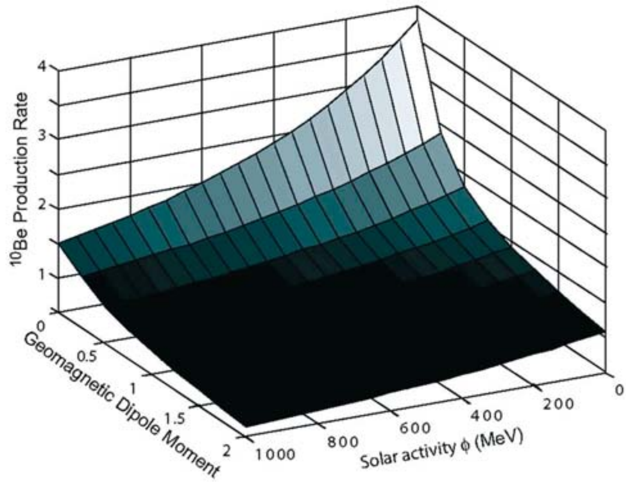

Figure 3. Calculated relative mean global production rate of ^{10}Be in the atmosphere as a function of solar activity expressed in terms of the modulation potential Φ, and the dipole moment of the geomagnetic field, relative to its present value. Φ = 0 MV corresponds to a very quiet Sun, Φ = 1000 MV to a very active one. The production rates are expressed relative to 0.018 ^{10}Be atoms cm^{-2} s^{-1} (from Ref. 6).

Figure 2 illustrates the measurement procedure used for ^{10}Be. First, a drilling machine obtains an ice core that can range from <200 m to >2000 m in length. The ice core is then divided into lengths corresponding to 1-8 years of snow accumulation, and the ^{10}Be extracted by chemical means from each sample[5]. The concentration of the ^{10}Be is then determined by using accelerator mass-spectrometry, and expressed as the number of ^{10}Be atoms per gram of ice.

The instrumental measurements since 1936 have shown that the cosmic-ray intensity is strongly affected ("modulated") by the strength and other properties of the interplanetary magnetic field and the solar wind. A quasi-theoretical quantity, the cosmic-ray modulation potential, Φ, has been defined that provides a useful quantisation of these effects[13]. Since the commencement of neutron monitor measurements in 1951, Φ has varied between 500 MV near sunspot minimum and 1200 MV near sunspot maximum. The geomagnetic field deflects the charged cosmic rays and thus prevents lower energy cosmic rays from reaching the top of the temperate and equatorial atmosphere. Consequently, the substantial variations in the strength of the geomagnetic field (±30-40%) in the recent past have had a strong effect upon the cosmic-ray intensity at Earth as summarised[6] by Figure 3. This shows that the ^{10}Be mean global production will vary by a factor of up to 10, for $0 < \Phi < 1000$ MV, and for the variability in the geomagnetic field determined from archaeomagnetic and paleomagnetic data (relative to the present dipole moment of the geomagnetic field).

The cosmogenic ^{14}C data exhibit a "memory" effect due to the long-term storage of the ^{14}C in the oceans and biosphere (the carbon cycle), and as a consequence they do not provide a direct measure of the cosmic radiation intensity at a specific time in the past[14]. In effect, the carbon cycle acts as a low-pass filter, whose response varies approximately as the reciprocal of frequency. After allowance for this frequency response, the ^{14}C data provides a sensitive record of the periodicities in the cosmic radiation in the past. A mathematical model of the carbon cycle can also be used to "invert" the observed ^{14}C data, yielding estimates of the rate of production of ^{14}C (and hence the cosmic-ray flux) as a function of time.

The cosmogenic ^{10}Be data have a much shorter memory effect, because the ^{10}Be is removed from the atmosphere after a mean residence time of about 1 year. As a consequence, they can be used directly as measurements of the cosmic-ray intensities in the past. Together, the ^{10}Be and ^{14}C data provide two independent measurements of the cosmic-ray intensity over extended periods of time. Different atmospheric processes are involved in storing the ^{10}Be in polar ice, and the ^{14}C in biological material, and intercomparison of the two methods allows solar and geomagnetic effects to be distinguished from atmospheric transport and climatic processes. In summary, the two cosmogenic nuclides, ^{10}Be and ^{14}C, exhibit a number of different characteristics, and when used together provide a quantitative understanding of the time dependence of the cosmic radiation in the past.

There are several external factors that introduce systematic and random errors into the cosmogenic measurements of the cosmic-ray intensity[6,7], and as a consequence the errors in the cosmogenic nuclide data are considerably larger than in modern instrumental cosmic-ray data. However, the primary role of the cosmogenic data is the investigation of the cosmic-ray intensity changes over time scales ranging from decades to millennia and above. Taking the case of 22-year averages of the ^{10}Be data, it has been shown that the standard deviation of individual 22-year averages is ~4.4%[15], while the decadal and century-scale variations due to solar processes are in the range 30 - 40% (see Fig. 4). Thus, while there are considerable errors in the data compared to their modern instrumental counterparts, the ^{10}Be data provides a very good "signal to noise" ratio for studying the long-term variability of the cosmic-ray intensity.

Against that background, we will now outline some of the advances that have occurred in recent years in the use of cosmogenic data to investigate the historic variations in the cosmic-ray intensity at Earth. In large part, these advances were refined and stimulated by the inter-community workshop "^{10}Be, ^{14}C, the Sun, and the Heliosphere" at ISSI in 2003.

The Cosmic-Ray Intensity during the Last Millennium

The top two panels of Figure 4 display the ^{10}Be data from Dye 3, Greenland, and the South Pole, for the interval 850 - 1950 AD. To emphasise the long-term secular changes, these data are 22-year running averages, spaced every 7 years[15]. While there are differences in the detailed variations in Greenland and Antarctica, it is clear that there is general agreement between the century-scale

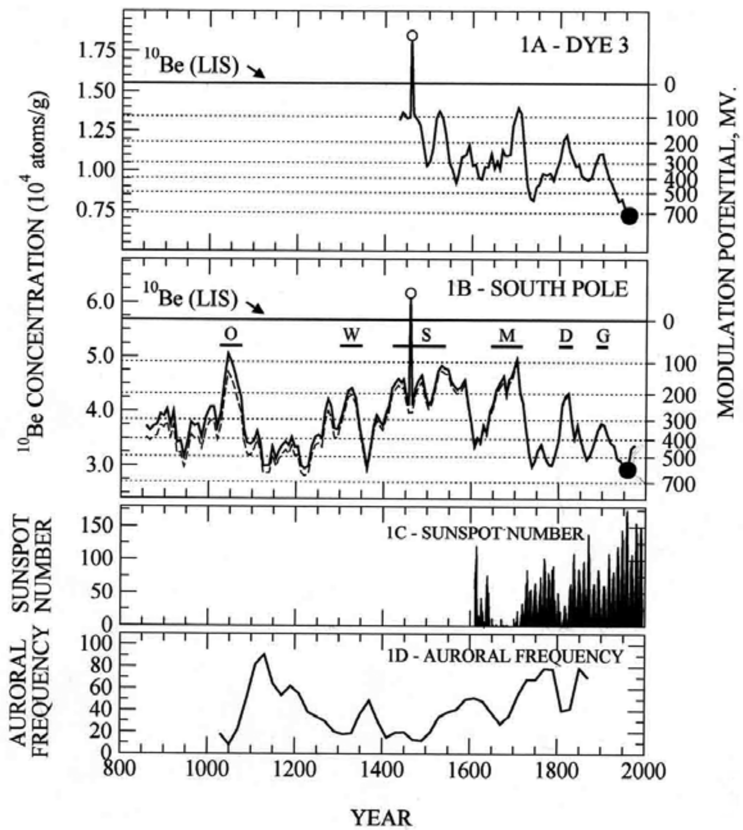

Figure 4. The temporal variation in the concentration of cosmogenic ^{10}Be observed in the Arctic ("Dye 3"), and the Antarctic ("South Pole"), for the interval 850 - 1950 AD, after compensation for the secular changes in the geomagnetic field. The concurrent sunspot and auroral record given in the lower panels show the manner in which solar activity has changed throughout the interval, as discussed in the text. The periods of low solar activity and their counterparts in the ^{10}Be records are identified as follows: O = Oort minimum; W = Wolf minimum; S = Spoerer minimum; M = Maunder minimum; D = Dalton minimum; and G = the Gleissberg minimum of ~1895. The lines labelled ^{10}Be(LIS) represent the estimated ^{10}Be concentrations in the absence of any solar modulation[15]. The right-hand scale gives the "modulation potential", Φ, as discussed in the text. The high points near 1460 are discussed in the caption to Figure 5 (from Ref. 15).

changes in the two records. As discussed above, we will now regard the ^{10}Be data as a measurement of the cosmic-ray intensity at Earth in the vicinity of 2 GeV/nucleon.

The historical sunspot record, and the mid-latitude auroral record are also displayed in Figure 4. As first inferred from ^{14}C data[16], the cosmic radiation intensity was high during the Maunder (1645 - 1715) and Dalton (1810 - 30) "grand minima" in the sunspot record, while it was ~40% lower during the intervening period of high solar activity. The rate of occurrence of mid-latitude aurora in the bottom panel of Figure 4 reflects the level of solar activity; modern experience shows that low frequencies of occurrence correlate with low sunspot numbers, and reduced solar activity. Figure 4 shows that the auroral activity was low in the vicinity of 1050 AD, 1320 AD and 1420-1500 AD (called the Oort, Wolf, and Spoerer grand minima, respectively), and that the ^{10}Be data attained high values similar to those during the Maunder and Dalton minima. In summary, Figure 4 shows that the cosmic-ray intensity has been high when solar activity was low, and that the intensity was ~40% lower during the intervening periods of higher sunspot numbers, and higher solar activity.

The geomagnetic field decreased[17] by ~25% in the period shown in Figure 4, and as a consequence, the ^{10}Be production rate increased by ~8.5 % throughout this period[15]. The dashed line in Figure 4 gives the observed concentration of ^{10}Be, while the solid line gives the ^{10}Be data after correction for the effects of these changes in the geomagnetic field. The solid line shows that there was no statistically significant change in the maximum cosmic-ray intensity at Earth between the maxima in 1050 AD and 1700 AD. That is, within the accuracy of these data, there is no evidence to suggest that the interstellar cosmic-ray intensity (i.e. outside the influence of the Sun's magnetic field) has changed over this interval[15].

The right-hand scales of Figure 4, and the dotted lines, indicate the manner in which the "modulation potential", Φ, has varied over time. The 22-year average values of Φ achieved low values (~100 MV) during the Oort, Spoerer, and the last part of the Maunder "grand solar minima", while the residual modulation during the Wolf and Dalton grand minima was substantially higher, in the vicinity of 200 MV. These results indicate that the cosmic-ray intensity at Earth during the Oort, Spoerer and last part of the Maunder minima approximated that in interstellar space, and that the interplanetary fields had little modulating effect upon the cosmic radiation incident on the heliosphere.

Since 850 AD the 22-year average cosmic-ray intensity (as measured by the ^{10}Be concentration) has returned repeatedly to low values that are similar to those of the present epoch (i.e. since 1950). Thus the ^{10}Be concentration at the South Pole

in Figure 4 exhibits minima within ±2% of 3.00×10^4 atoms/g for the 22-year averages centred on 940, 1132, 1220, 1360, 1740, and 1958 AD. This remarkable result indicates that the modulation process, and by inference, the properties of the heliospheric magnetic field, were similar during many of the periods of high solar activity between 850 and 1958. This may indicate that the interplanetary magnetic field near Earth is presently near an asymptotic value that it has approached on five previous occasions in the past 1150 years[26].

Figure 4 shows that the neutron-monitor era (1951-date), and the satellite era (1963-date) both represent one of the most extreme cosmic-ray modulation events in the past 1150 years[15,18]. Thus while the satellite and other cosmic-ray data provide us with a very detailed knowledge of the present-day three-dimensional heliosphere, this is not the typical condition of the heliosphere over the past millennium. This emphasizes the role of the cosmogenic nuclide data, in that they provide us with the means to explore the cosmic-ray modulation processes (and the level of solar activity) over time-scales of thousands of years, and during times when the heliosphere was significantly different from the present epoch[18].

The Cosmic-Ray Intensity during the Spoerer Grand Minimum

The cosmic-ray intensity maximum in the interval 1420 - 1540 (the Spoerer minimum) was the most prolonged in the past 1150 years (see Fig. 4). We study this interval in greater detail, to better understand the cosmic-ray modulation effects during a prolonged "grand minimum" of solar activity[15]. In effect, we use it as a "virtual laboratory" that allows us to investigate the quiet Sun. Figure 5 presents the annual ^{10}Be data from Greenland for the interval, 1420 - 1540. There was persistent and relatively large amplitude (~25%) modulation of the cosmic radiation throughout the whole interval. The persistent ~25 year repetition indicates the continuation of the 22-year periodicity in the solar magnetic field. Note also the 11 and ~5-year repetitions; the latter having been reported previously[19,20]. Annual measurements of tree ring ^{14}C exhibit an 11-year variation that confirms the presence of this modulation at this time[21].

The cosmic-ray intensity first attained a value close to the interstellar value (the line marked $^{10}Be(LIS)$) at the beginning of the Spoerer Minimum, and then returned repeatedly to values that are statistically consistent with that value until 1530. These observations indicate that: (1) the heliosphere repeatedly returned to a condition of very low residual cosmic-ray modulation throughout the

Spoerer Minimum, 1420 - 1540, and (2) the cosmic radiation experienced solar control at both the 11- and 22-year periodicities. These cosmogenic cosmic-ray data provide a clear indication that solar activity continued in an episodic manner throughout this grand minimum, and provide a better insight into that period than is possible using the scanty historical sunspot and auroral records from that era. The continuation of cosmic-ray modulation through a portion of the Maunder minimum (1645 - 1715) has been established as well[15,18,22]. These results emphasise the important property of the cosmogenic cosmic-ray data to provide the means to investigate the 11- and 22- year solar variability far into the past.

The Cosmic-Ray Variability over the Past 10 000 Years

The ^{10}Be data in Figures 4 and 5 have allowed the cosmic-ray variations recorded in the cosmogenic record to be compared with those in the instrumental record. The availability of a detailed sunspot record since 1610; and sparse sunspot and auroral records prior to that, have allowed the relationship between solar activity and the cosmic radiation intensity to be established with some confidence. In general, (a) the highest cosmic-ray intensities, which indicate a 22-year average modulation potential of ~100 MV, correspond to extended periods

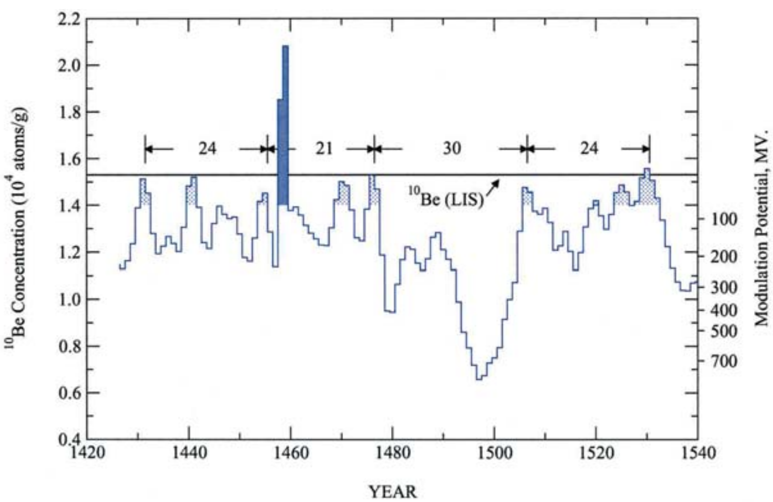

Figure 5. The ^{10}Be concentration at Dye 3, Greenland, corresponding to the Spoerer minimum in solar activity. The line labelled ^{10}Be(LIS) represents the estimated ^{10}Be concentration in the absence of any solar modulation[15]. The right-hand scale gives the modulation potential derived from these data, and it shows that the heliospheric field continued to modulate the cosmic radiation throughout this whole period. The two extreme points in the vicinity of 1460 are proposed to be due to the production of cosmic rays by the Sun, or by gamma rays from a nearby supernova (from Ref. 15).

(> 50 years) of low solar activity; while (b) the lowest cosmic-ray intensities, corresponding to a 22-year average modulation potential of ~700 MV, are associated with a very active Sun, as in the modern epoch 1950-2000. This provides a "calibration" that allows us to use the ^{10}Be and ^{14}C archives to study both the cosmic radiation intensity, and the degree of solar activity in the past, and to compare it to the past 1000 years summarised in Figure 4. Stimulated, in part, by the 2003 ISSI workshop, there is now active interest in using cosmogenic records to investigate the cosmic-ray (and thence, solar) effects in the past. The following is an outline of the progress made, and an indication of the progress that will be made in the near future.

The ^{10}Be signal found in ice cores reflects not only production changes, but also changes in the atmospheric transport and deposition processes. During periods when the climate is relatively stable, such as the past 12,000 years (the Holocene), these effects are generally much smaller than the production effects. This is not the case for glacial times when the accumulation rate of ice has been smaller by up to a factor of 2, yielding higher ^{10}Be concentrations. Further, the mixing effects in the oceans are believed to have changed during glacial times, thereby changing the "filtering" characteristics of the carbon cycle. For this reason, we will first consider the post-glacial period in this section, and then briefly consider part of the glacial period in the next section.

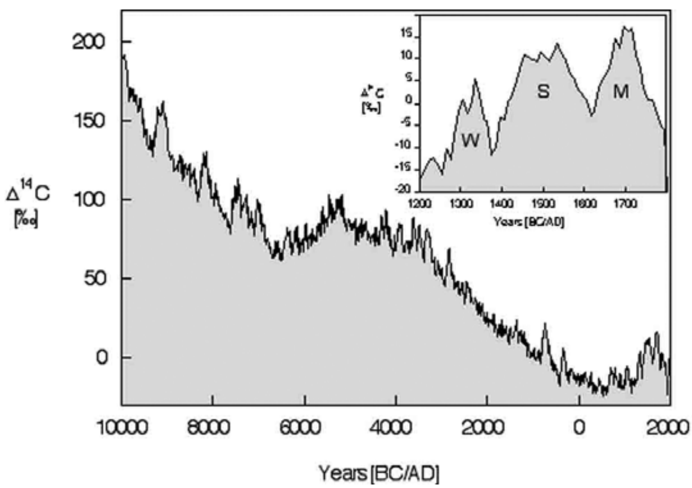

Figure 6. The cosmogenic ^{14}C data corresponding to the interval 10,000 BC to 1950 AD. The inset is for the interval 1200 - 1800 AD. Note that the century-scale variations in the inset are similar to those in Figure 4, corresponding to the Wolf (W), Spoerer (S) and Maunder (M) minima. These and the other century-scale variations are superimposed on a changing baseline due to the long-term changes in the strength of the geomagnetic dipole.

Figure 6 displays the ^{14}C data for the past 12,000 years[19]. This record consists of relatively short-term (~200 year) variations superimposed upon a long-term, slowly changing baseline. The latter is largely due to the long-term changes in the cosmic-ray geomagnetic cut-off, as a consequence of the ±30 - 40% changes in the Earth's dipole moment over the past 20,000 years.

The inset in Figure 6 displays 600 years of the ^{14}C record. It represents the same sequence of cosmic-ray fluctuations (from the Wolf to the Maunder events) that were evident in the ^{10}Be record in Figure 4, superposed upon a steady increase due to the "memory effect" discussed previously. There are other episodes of short-term (~200-year) enhancements in the 12,000 year ^{14}C record in Figure 6, of similar duration and amplitude to the Wolf-Maunder sequence in the inset. The "calibration" at the beginning of this section therefore suggests that the cosmic radiation has experienced a number of sequences of ~200-year modulation events over the past 12,000 years, similar to those in Figure 4, as a consequence of changes in the level of solar activity. Based upon this association, Figure 6 suggests that: (a) the Sun remained active for the 2000 year interval 2800-800 BC, without periods of low solar activity similar to those observed during the recent millennium (Fig. 4); (b) that by way of contrast, there were a number of "grand minima" in the 1200 year interval 4400-3200 BC; and (c) there were a number of substantially longer periods (~500 yr) of very low solar activity in the interval 9500-6600 BC.

In summary, the cosmogenic ^{10}Be and ^{14}C data now provide the means to make quantitative studies of the time variations in the cosmic radiation at Earth in the post-glacial period since 10,000 BC. The initial studies have demonstrated that there have been a number of modulation episodes similar to the Oort-Dalton sequence during that time. Several new ice cores have been drilled in recent years that include the post-glacial period, and these will allow more detailed analysis of the cosmic radiation intensities throughout this period.

The Cosmic-Ray Variations during the Past 60 000 Years

Astronomical observations indicate that the magnetic fields and gas density in interstellar space in the vicinity of Earth have varied substantially over the past 100,000 years[23]. This suggests that the cosmic-ray intensity near Earth may have varied as a consequence of the Earth's motion about the centre of our Galaxy, and if so it would provide important information regarding the structure of the Galaxy. In addition, there is the possibility that a supernova may have resulted in enhanced cosmic-ray intensity at Earth in the past. The cosmogenic measurements of the cosmic radiation allow both possibilities to be investigated.

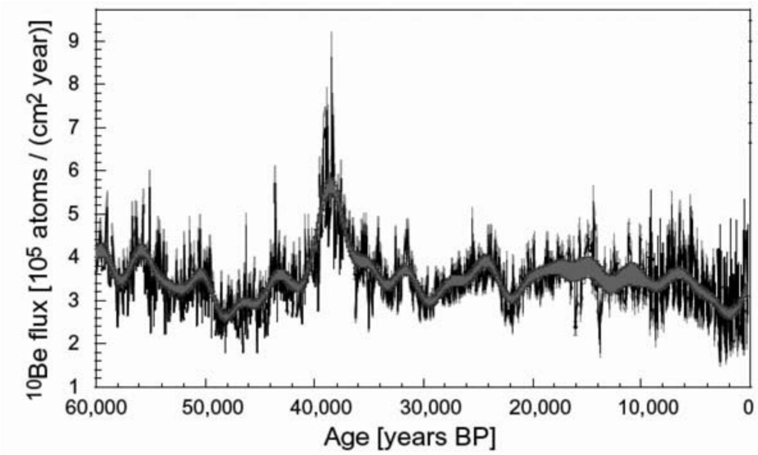

Figure 7. The ^{10}Be flux estimated from an ice core from Greenland, corresponding to the past 60,000 years BP (means years before 1950). The individual data points are 100-year averages, and the central line is the 3000-year running average of those data (from Ref. 24).

Figure 7 displays the ^{10}Be precipitation rate over the past 60,000 years. The period prior to 12,000 BP ("before present") corresponds to the last glacial epoch, when the accumulation rate of ice was smaller, resulting in higher ^{10}Be concentrations, which might be misinterpreted as higher cosmic-ray intensities. A number of the concurrent measurements in the ice cores yield estimates of the snow precipitation rate, allowing the ^{10}Be flux (i.e. the annual ^{10}Be precipitation rate) to be calculated, and this provides a measurement of the cosmic-ray intensity unaffected by the severe climate changes between the glacial and post glacial periods. Figure 7 shows that there were substantial changes in the ^{10}Be flux throughout the past 60,000 years, and we now briefly discus two of the more prominent variations: (1) the broad minimum in the vicinity of 5000 - 1000 BP; and (2) the high values in the interval 40,000 - 37,000 years before the present.

As discussed previously, Figure 3 implies that variations in the strength of the geomagnetic field result in out-of-phase variations in the cosmic-ray intensity at Earth. Paleomagnetic studies show that the geomagnetic dipole moment was low ~6,000 years ago (75% of the present value), that it attained a maximum 3,000 years ago that was 40% above the present value, and that it has declined rapidly over the past 1000 years. The relationship between the cosmic-ray intensity and the geomagnetic dipole strength is well-known (see, for example, Fig. 3), and fully explains the reduction in ^{10}Be flux in the interval 5000-1000 BP in Figure 7.

Measurements of the remnant magnetism in sea sediments have shown that the geomagnetic field reached an intensity minimum of 10-20% of its present value

about 40,000 BP, and that it was close to reversing its polarity for a period of ~5000 years[24] (called the "Laschamp magnetic event"). Figure 3 indicates that the ^{10}Be flux to Earth would therefore increase by a factor of 2 - 2.5, which is consistent with the observations in Figure 7. Both of the variations in the ^{10}Be flux considered above are therefore consistent with independent paleo-magnetic measurements, and other mechanisms are not required to explain them. Nevertheless, data such as in Figure 7 will be important to set limits on the effects due to changes in the Earth's interstellar environment, supernova explosions, interstellar shock waves, and extended periods of low solar activity in the past.

Inferred Properties of the Interplanetary Magnetic Field and Solar Activity in the Past

The majority of the cosmic radiation observed at Earth originates in the Galaxy, and reaches Earth after propagating through magnetic fields of solar origin that extend to the limits of the heliosphere, some 100 - 150 Astronomical Units from the Sun (1 AU = the Sun–Earth distance). The "cosmic-ray transport equation" describes the cosmic-ray propagation processes in terms of the properties of the heliomagnetic field, and the speed of the solar wind, and this shows that the intensity of the galactic cosmic radiation at Earth is determined by these several properties[25]. That is, the cosmic-ray intensity at Earth can be regarded as a measurement of the integrated properties of the heliospheric magnetic fields. Since the cosmogenic ^{10}Be data constitutes a measurement of the cosmic-ray intensity, they can be used to investigate the properties of the heliospheric magnetic field in the past. The initial studies of this field were based on extrapolations from the present, using statistical regressions between the sunspot number and ^{10}Be data to guide the extrapolation[12].

By inverting Parker's cosmic-ray transport equation[25], the cosmogenic ^{10}Be data given in Figure 4 have been used recently[26] to investigate the strength of the heliospheric field at Earth since 850 AD. These studies show that the 22-year average magnetic field was lowest (2 - 3.75 nanotesla, nT) during the Oort (1050 AD), Spoerer (1420 - 1540 AD) and the latter part of the Maunder minima. During each of the periods of high solar activity since 850 AD (Fig. 4), the 22-year average field was similar to the present-day value (~6 nT). Satellite measurements show that the 3-month average field has varied[29] over the range 5-10 nT since the 1960s. Together, these results suggest that the heliospheric field near Earth may vary by a factor of 3 - 5 between a grand minimum and the periods of enhanced solar activity.

A number of extrapolations of the sunspot number into the past have been made using empirical models of the correlation between sunspot number and the cosmic-ray intensity[27, 28]. Considerable progress in such studies, and companion extrapolations of the solar irradiance into the past, is to be expected using the cosmic-ray production rate based on ^{14}C, and ^{10}Be from several recently acquired ice cores.

Conclusions

Stimulated by the two ISSI workshops[4] in 1999 and 2003, there has been considerable progress towards using the cosmogenic nuclides to study the manner in which the galactic cosmic radiation at Earth has varied over historic time. These studies have determined that they represent a measurement that is broadly similar to that of a neutron monitor, but corresponding to somewhat lower cosmic-ray energy. Using ^{10}Be data, the cosmic-ray modulation potential has been estimated for the 1150-year period since 850 AD. This shows that the cosmic-ray intensity is highest during the "grand minima", approaching the intergalactic intensity that exists outside the heliosphere. The modulation effects of the heliospheric magnetic fields are considerably higher during periods of substantial solar activity. Using the cosmic-ray transport equation, the ^{10}Be data for the period 850-1950 have been inverted to yield estimates of the temporal variation of the strength of the heliospheric magnetic field at Earth. They show that the heliospheric field near Earth was in the range 2-3.75 nT during prolonged periods of low solar activity such as the Spoerer minimum, while satellite measurements show that it has been in the range 5-10 nT since 1960.

With the availability of a number of new ice cores, and further development of the methodology to interpret the cosmogenic data as cosmic-ray intensities, it is anticipated that there will be considerable advance in the study of "paleo-cosmic rays" in the near future. Further, the ^{10}Be and ^{14}C data themselves, and the inferred cosmic-ray parameters (such as the modulation potential), will be used increasingly to examine the properties of the interplanetary field, and the temporal variation of solar activity over the past millennia[28].

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