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The Variable Nature of the Galactic and Solar Cosmic Radiation over the Past 10,000 Years

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Abstract. The galactic and solar cosmic radiation in the inner solar system have left indelible records of their varying intensities over the past millennia in ice cores, tree rings, and meteoritic material. While this was previously well known, atmospheric, meteorological, and other factors have hindered the use of these data in quantitative studies of the cosmic radiation. This is no longer so due to two recent and independent developments. They are (1) the use of mathematical codes based on GEANT, modern signal processing, and global climate models to understand the rigidity responses, and reduce the geomagnetic and atmospheric interference with the cosmic ray signal; and (2) the use of the instrumental record 1933-2006, and our theoretical knowledge of the heliosphere and the cosmic ray modulation, as a "Rosetta Stone" to decipher the paleo-cosmic ray record. Together, these have shown that the intensity of the < 10 GeV galactic cosmic radiation (GCR) has varied strongly over the last $> 10{,}000$ years. The intensity of the GCR has been very low since 1954, while it was much higher as recently as 1895 AD. The intensity in $\sim$1450 AD was consistent with the local interstellar spectrum being incident on Earth (i.e., no modulation). Over the past decade it has been established that large solar energetic particle (SEP) events have left discernible records in the nitrate content, and more recently, the ^{10}Be content of ice cores. Analyses of these data since 1572 reveal a counter-intuitive result- that large SEP events were more common at times of relatively weak solar cycles (e.g., circa 1895) compared to the present epoch. The solar magnetic flux is estimated to have been 50% of its present-day value in $\sim$1895 AD , suggesting that the Alfven velocity in the corona was half its present day value, resulting in more efficient acceleration of solar energetic particles. Solar and geomagnetic studies suggest that there will be a "Gleissberg Minimum" (i.e., several decades of lower solar activity) in the near future and it is predicted that then (1) the GCR intensities will be a factor of ~ 2.25 times higher at 1GeV and (2) the frequency of occurrence of large SEP events will increase five-fold.

Introduction

It has been long recognized that the galactic cosmic radiation has left indelible records of its varying intensity in ice cores, tree rings and meteoritic material. More recently, records of the production of solar cosmic radiation have been recognized in ice cores as well. Until recently, however, these paleo-cosmic ray records had not been inter-calibrated to instrumental ground level and satellite measurements. Furthermore, they seemed, in part, to be at variance with the behaviour of the cosmic radiation since $\sim$1950. As a consequence they have been regarded with some suspicion by the cosmic ray community, and they were little used to study the cosmic ray processes in past centuries and millennia. Worse still, the cosmogenic data were frequently used in other disciplines without the benefit of the technical knowledge that the cosmic ray community could provide.

Over the past decade, modern mathematical models have allowed the paleo-cosmic ray data to be inter-calibrated to the modern instrumental measurements. Other mathematical models are rapidly removing past uncertainties regarding the averaging processes in the atmosphere prior to sequestration of ^{10}Be in polar ice and ^{14}C in biological material. As a consequence, there has been considerable progress in the joint use of the instrumental and paleo-cosmic ray records in cosmic ray studies, and in related geophysical and astronomical studies.

This paper reviews the present status of these several matters. It commences with a outline of

SOURCES OF PALEO-COSMIC RAY DATA

GALACTIC COSMIC RADIATION	
- ^{10}Be	(Icecores)
- ^{14}C	(Tree rings and other biological materials)
- ^{44}Ti	(meteoritic material)
SOLAR COSMIC RADIATION	
- Nitrates	(Icecores)
- ^{10}Be	(Icecore)

Table 1.

THE PIONEERS

In the beginning	B. Peters and D. Lal. W. Libby
The Systemisers	G. Castagnoli and D. Lal U. Siegenthaler and H. Oeschger
The Data Gathers and Analysts	M. Stuiver and P. Damon (^{14}C) J. Beer, G. Raisbeck, F. Yiou (^{10}Be) S. Forbush, V. Neher, & J. Simpson G. Dreschhoff and E. Zeller (nitrates)

Table 2.

the paleo-cosmic ray data themselves, with a brief attribution to the early pioneers in this field. It then discusses the use of mathematical models to intercalibrate the past to the present, and in the investigation of other features of the paleo-cosmic ray record. A review follows of our present knowledge regarding the long term (10,000 years) changes in the intensity of the galactic and solar cosmic radiation. Then there is a brief review of the use of the paleo-cosmic ray record to study geophysical, space weather, astronomical, and other questions. Finally, it outlines desirable theoretical and data acquisition initiatives for the future, and speculates regarding advances that may be expected in the next ten years or so.

The Paleo-cosmic ray records

Table 1 summarizes the most common forms of paleo-cosmic ray data, while Table 2 lists the early pioneers who first recognized, and then developed the data archives that are at our disposal today.

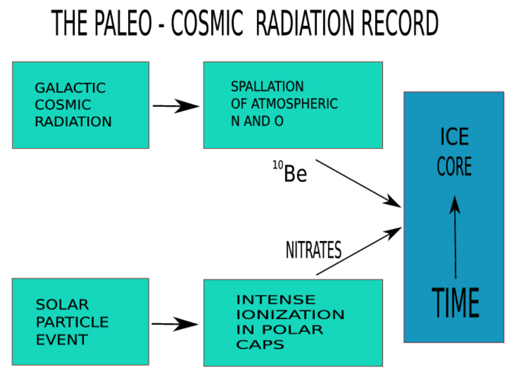

Fig. 1. Illustrating the origin of the ^{10}Be and nitrate paleo-cosmic radiation signals in ice cores from the polar regions.

Fig. 1 displays the mechanisms leading to the GCR and solar energetic particle (SEP) records in polar ice. On colliding with the nucleus of an atmospheric atom, a cosmic ray initiates a spallation reaction that produces ^{10}Be, ^{14}C, and other fragments. Both ^{10}Be and ^{14}C are radioactive nuclides, whose presence on Earth is totally due to these cosmic ray induced reactions [1].

The ^{10}Be atoms attach themselves to atmospheric aerosols, and remain suspended in the atmosphere for approximately one year before precipitating to Earth. In the polar regions the annual ice layers are clearly defined, and the ^{10}Be precipitated in any given year is determined using atomic mass spectrometry. Atmospheric mixing, weather related effects, and changes in the geomagnetic field superimpose variations into the ^{10}Be record in addition to the GCR signal, as discussed later. Recently, it has been recognized that there is a detectable solar cosmic ray signal in the ^{10}Be record. Extremely large SEP events are now known to produce up to 10% of the annual flux of ^{10}Be to the polar caps, however this is only barely discernible due to the statistical variations in the present-day annual ^{10}Be data [2]. Several new ice cores are being analysed at present, and when combined with the presently available data, large SEP events will be clearly evident in the historic record.

W. Libby was the first to discuss the use of a cosmogenic nuclide (^{14}C) to date biological material, and it was soon recognized that there were variations in the ^{14}C data (the "Suess wiggles") that are now known to be due to long term variations in the GCR spectrum. The possibility of using ^{10}Be (and other radionuclides) to study the variations in both the galactic and solar cosmic radiation was first discussed by Lal and Peters [3]. Castagnoli and Lal [4] later provided a detailed analytical framework that took account of geomagnetic effects, and the 11- year modulation. Seigenthaler et al. Siegenthaler et al. [5] developed a methodology to describe and evaluate the time averaging effects of the carbon cycle, which results in long-lived storage of the ^{14}C in the oceans and biological materials.

Techniques for the measurement of ^{14}C became well established in the 1970s, and major archives were established by Stuiver and Damon. Practical utilization of ^{10}Be as a measure of the cosmic ray intensity only became possible following the development of atomic mass spectrometry in $\sim$1980. Beer, Raisbeck and Yiou ([6], and references therein) have been the main contributors to the ^{10}Be archive used in cosmic ray studies since that time.

As is well known to the cosmic ray community, Forbush, Neher, and Simpson pioneered the instrumental measurements using ionization chambers (pre 1951) and neutron monitors (post 1951). Simpson and his collaborators (e. g., [7]) then pioneered the analytical background that has allowed study of the characteristics of the several temporal variations in those data.

In the 1980s, Dreschhoff and Zeller [8] showed that there were large, short lived ($<$ 2 month) enhancements in the nitrate stored in polar ice, and that several correlated with intense solar energetic particle (SEP) events. Jackman and co-workers ([9],[10]) later showed that this was explicable in terms of the intense ionization produced by SEP events in the polar caps. This is discussed in more detail in the next section. Dreschhoff and Zeller [11] obtained a high resolution nitrate record from a 210 m core obtained in Greenland that has provided SEP data from 1572.

Meteoritic and lunar material has provided additional information that augments the above sources of data. The ^{44}Ti in meteorites has provided a record of the temporal variability of the GCR over the past 3 centuries; this is important because it does not contain atmospheric effects such as are present in both the ^{10}Be and ^{14}C records [12]. The induced radioactivity in lunar material has provided upper limits for the occurrence of extremely large SEP events in the past [13]. Neither of these sources will be discussed further, however they have provided useful confirmation (and limits) for the studies based on ^{10}Be, ^{14}C, and the nitrate record.

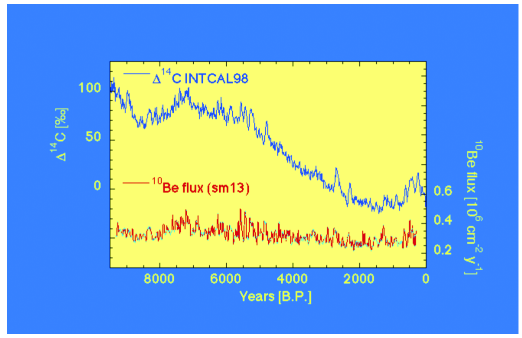

Fig. 2. Comparison of the ^{14}C and ^{10}Be observations prior to correction for the integrating effects of the atmosphere and oceans on the ^{14}C data. Time BP refers to "Time Before Present", meaning the year 1950. [With thanks to J.Beer].

Calibration to the Instrumental Record-Galactic Cosmic Radiation

Fig. 2 displays the ^{10}Be and ^{14}C records for the past 10,000 years. The rather striking differences have long been understood in general terms to be due the greatly different residence times of the two nuclides in the atmosphere and oceans, however quantitative agreement was difficult to establish. Further, the ^{10}Be data at sunspot minimum showed a slow $\sim 40\,\%$ decline between 1900 and the commencement of the neutron monitor record in 1951 that appeared to be the be at variance to the approximate constancy of the neutron record at sunspot minimum since 1951. Stated simply, the three separate cosmic ray records needed to be reconciled to one another.

The advent of detailed mathematical models in the late 1990s solved this problem in a rigorous manner. Using the GEANT code, Masarik and Beer [14] simulated the development of nucleonic cascades at all geomagnetic latitudes, as a function of the strength of the geomagnetic dipole, and the

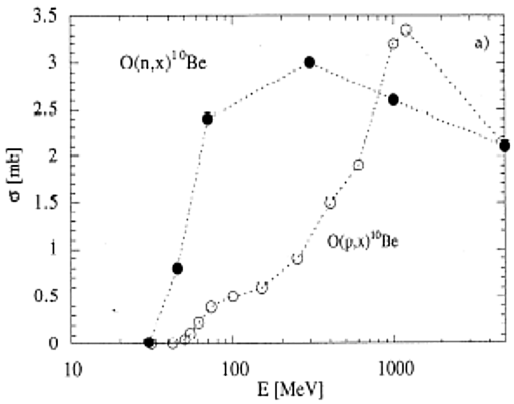

Fig. 3. The nuclear cross-sections of two of the spallation processes that give rise to the radioactive nuclide ^{10}Be [14].

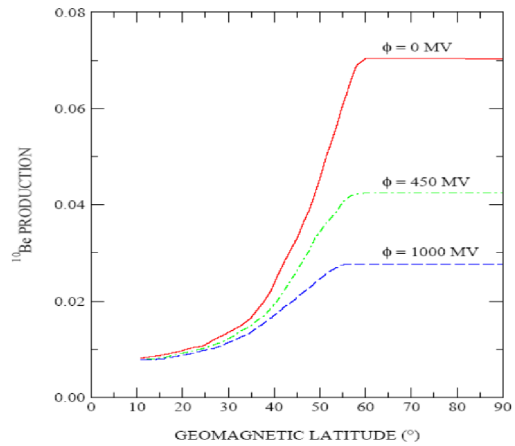

Fig. 4. The dependence of the ^{10}Be production rate upon geomagnetic latitude computed using the GEANT nuclear propagation code [14].

prevailing level of solar modulation. In this, they used known cross-sections of the several interactions similar to those is Fig. 3. Fig. 4 demonstrates the results obtained for ^{10}Be for modulation potentials of 0, 450, and 1000 MV, for the present-day geomagnetic moment. These curves (and those for the other cosmogenic nuclides) are formally similar to the "latitude curves" obtained for neutron monitors and other instrumental detectors; the Masarik and Beer results were later converted into response functions by McCracken [15]. Independently, Webber and Higbie [16] used the FLUKA code to compute specific yield functions similar to those presented in Fig. 5. These two sets of functions provided, for the first time, the ability to compute the changes that occur in the cosmogenic nuclides for given changes in the (a) modulation potential; (b) local interstellar spectrum; and (c) the geomagnetic field. Using similar simulations for neutron monitors [17] and ionization chambers [18] based on GEANT/ FLUKA, McCracken and Beer [2] have determined the inter-calibration curves for ^{10}Be, neutron monitors, and ionization chambers given in Fig. 6. Note that these curves are substantially non linear, as a results of the cosmic ray modulation varying approximately as the reciprocal of rigidity, and the substantially different rigidity sensitivities of the several types of measurements. Using them, McCracken and Beer [2] have inter-calibrated the instrumental measurements of the past 70 years, and the cosmogenic ^{10}Be data for the previous 5 centuries. The results are displayed in Figs. 7 and 8, and will be discussed further in a later section. It is stressed that the inter-calibrations of the different records are based totally on the cross-sections of the nuclear interactions that lead to the several forms of cosmic ray observations - avoiding all the major uncertainties associated with the use of regression techniques used in the past. This development is one of the most profound in the past decade, and places the long-term study of the cosmic radiation on a sound basis for the first time. Three other developments have contributed to our present-day ability to use the cosmogenic data to study the galactic cosmic ray intensity at Earth over the past millennia. They are:

- The use of Global Circulation Models (GCM) to determine the latitudes that contribute to the ^{10}Be observed in ice in the polar caps. This is a vital calibration step, as discussed below.

- The use of archeomagnetic data to estimate the strength of the geomagnetic dipole in the past, and thence the cut-off rigidities that determine the ^{10}Be and ^{14}C production rates, worldwide. This allows the long term trends due to the secular changes in the geomagnetic field to be removed from the data.

- The use of modern signal processing techniques to estimate the annual production rate

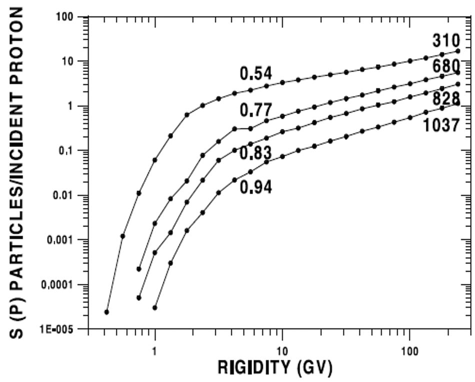

Fig. 5. The specific yield functions for neutron monitors at atmospheric depths of 310, 680, 828, and 1,037 g/cm^2. Similar curves were generated for all the cosmogenic nuclides using the FLUKA modeling code [16].

of ^{14}C from the observed data- that is- to remove the averaging effects imposed by the global carbon cycle.

To relate the observed changes in the ^{10}Be in the polar caps to quantitative changes in the cosmic ray spectrum (and changes in the modulation potential) requires that we know the extent to which the atmosphere is mixed prior to precipitation of the ^{10}Be. That is, we need to know how much of the ^{10}Be produced near the equator (high cut-off rigidity and smaller percentage modulation) is averaged with that produced near the poles (low cut-off). Further, we need to know whether this averaging process is different during the "little ice ages" compared to the present period of warmer climate, and perhaps, throughout the 11-year cycle of solar activity. Atomic mass spectrometry usually measures the concentration of ^{10}Be in the polar ice. That is, any annual data point, say, depends on both the amount of ^{10}Be and the mass of snow that has been precipitated during the year. As a consequence, year to year variations, and long term changes in the snow fall may introduce variations into the data record that are not representative of changes in the cosmic ray intensity [19]. In some cases, 18O or deuterium measurements have been used to identify the seasonal changes throughout the year, and thence the amount of water is estimated, allowing the "flux" of ^{10}Be to be computed. Averaging processes that filter out the more pronounced meteorological periodicities have also

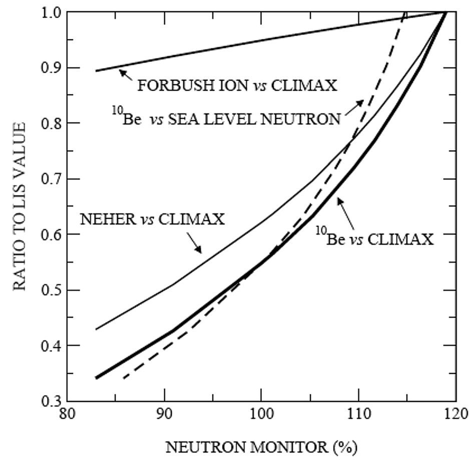

Fig. 6. Conversion curves between several important cosmic ray records, illustrating the non-linearity due to the different rigidity sensitivities of the measurement techniques [2].

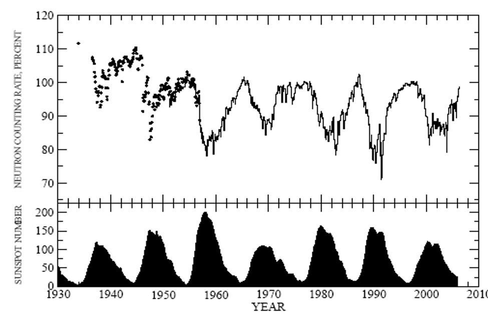

Fig. 7. The instrumental cosmic ray record, based on balloon borne and ground based ionization chambers prior to 1951, and neutron monitor data thereafter [2].

been used to minimize this source of "noise" in the data. The advent of detailed "Global Circulation Models" (GCM) has provided the means to minimize these problems in a quantitative manner. Using a GCM, Field et al. [20] have computed Fig. 9 which shows the worldwide precipitation of ^{10}Be; and it is immediately clear that this is non- uniform, with the greatest precipitation occurring in mid-latitudes. Using these results, Field et al. [20] have determined the "attenuation" of the modulation observed in polar ice as a result of the contributions from lower latitudes. Their work, and other GCM studies now in progress, are examining

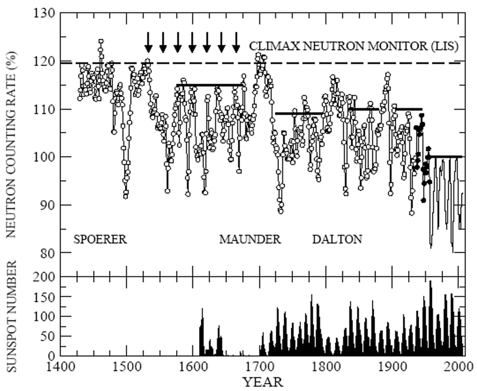

Fig. 8. The estimated counting rate of a neutron monitor with a cut-off rigidity of 3.15 GV, based on cosmogenic ^{10}Be data, and the instrumental record given in Fig. 7. The horizontal bars indicate suggested levels of residual modulation [2]

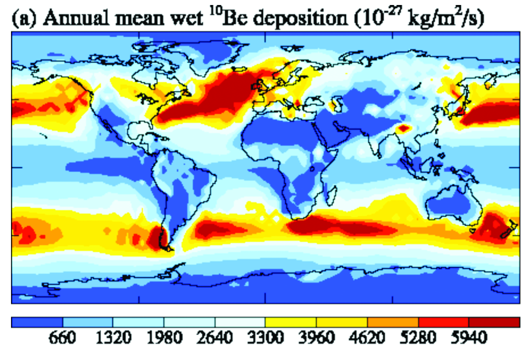

Fig. 9. Computation of the worldwide deposition rates of 10Be in the present epoch, obtained using a detailed global circulation model (GCM) to determine the mixing effects within the atmosphere prior to deposition [20]

the manner in which the "attenuation" varies with climate change, such as from the Maunder Minimum, to the present. The GCMs also provide information on the manner in which the precipitation of water has varied over the long term. In summary, the use of GCMs over the past several years has begun to remove the most important remaining uncertainty in the utilization of the cosmogenic ^{10}Be data to extrapolate the modern instrumental measurements back in time. Two techniques have been developed to determine the time dependence of the rate of production of ^{14}C from the observed data (which represents an integral of the production rate over the past > 5000 years). One consists of inversion of a mathematical model of the "carbon cycle", including the effects of the biosphere and the oceans, to compute the time dependence of the production rate that yields the observed data (e.g., [21]). The other consists of a Fourier transform method that filters out the longer term periodicities [22]. Fig. 10 compares the results of the ^{14}C inversion method, with the ^{10}Be for the past 10,000 years (the post glacial period- the Holocene). It is clear that there are clear similarities; the long term periodicity is due to the long term changes in the cut-off rigidity as a consequence of the secular changes in the strength of the geomagnetic dipole. The short term variations (time scales $\sim$100 years) are due to the time dependent solar modulation, and will be discussed later. The limited statistics, and residual errors due to meteorology, etc, mean that the 22-year average ^{10}Be data have a standard deviation of $\sim$4%. There are a number of new ice cores being analysed at present, and those, together with the inverted ^{14}C data, and the principal components technique discussed elsewhere in this conference [Beer et al., 2007], will result in a factor of approximately two reduction in the standard deviations over the next several years.

The nitrate and cosmogenic paleo-records of solar energetic particle events

As outlined above, Zeller and Dreschhoff pioneered high resolution ($\sim$ monthly) measurements of the nitrate in polar ice, and noted correlations with the Carrington white light solar flare of 1859 (Fig. 11), and several of the ground level events observed with ionization chambers. There are a number of sources of nitrate in the Earth"s atmosphere, and there are substantial inter-latitude mixing and meteorological effects, and as a consequence these correlations were not sufficient to establish a causal relationship between cosmic ray intensity, and the nitrate observations. Jackman et al. [9] provided the means to validate this relationship. Using the Goddard Space Flight Centre atmospheric transport model, and satellite observations of several

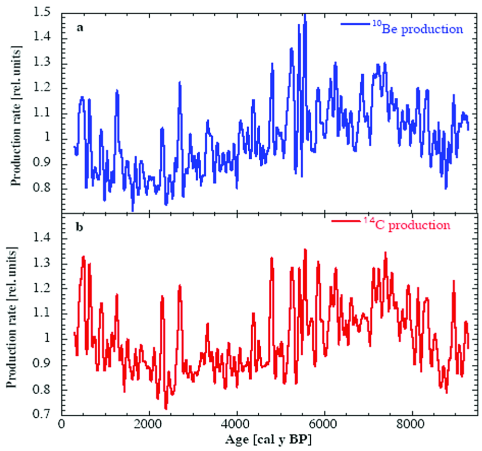

Fig. 10. Comparison of the computed ^{10}Be and ^{14}Cproduction rates for the previous 9500 years. The long term changes are due to changes in the Earth's magnetic field; the shorter term changes are due to the interplanetary modulation of the galactic cosmic rays. Note time in "before present"; i.e., running backwards. [Beer et al, this conference].

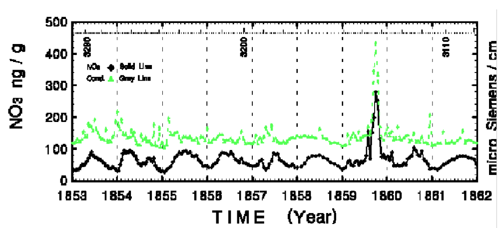

Fig. 11. The well dated high time resolution nitrate data from Greenland showing a large enhancement at the time of the white light flare observed on 1 September 1859 by Carrington and Hobson [11]. The annual variation is due to variable transport of nitrate produced by photoionisation processes at low latitudes.

large SEP, they computed the concentrations and time dependence of the nitrate in the polar atmosphere from all significant sources. They showed that the SEP caused major, short term changes compared to the annual variation due to transport of nitrate from lower latitudes. Using their computations, McCracken et al. [23] obtained a calibration between nitrate concentration, and SEP fluence. This was then used to estimate the fluence of 121 impulsive nitrate events corresponding to the period 1572-1950. These yielded the cumulative frequency of large SEP given in Fig. 12; the

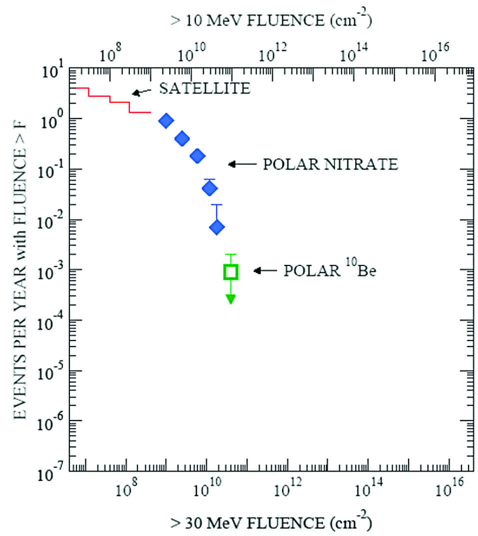

Fig. 12. The observed cumulative probability of occurrence of SEP events. From McCracken et al. [24], with ^{10}Be point added.

good agreement with the satellite data for lower fluences providing further validation that the impulsive nitrate events represent SEP that have occurred in the past. Lal and Peters [3] predicted that the cosmic rays from very large solar flares would generate a detectable signal in the cosmogenic record, and Masarik and Reedy [25] came to the same conclusion using the simulations based on GEANT summarized above. However the predicted increases were comparable with the ^{10}Be standard deviations, and validation of these predictions was not possible using the instrumental record obtained since 1936. The ^{10}Be data at the time of six very large SEP in the interval 1892-1898 [26]; analyses by Usoskin et al. [18]; and recent calculations of the ^{10}Be specific yield functions down to 20MeV [27] indicate that the largest SEP in the recent 400 years have resulted in up to 10% increases in the annual ^{10}Be record. As outlined above, these will become more evident in the ^{10}Be record when averaged over the several cores that are being analyzed at present.

The Cosmic Ray Rosetta Stone

The neutron monitor and satellite eras have been periods of high solar activity, while solar, geomagnetic and the cosmogenic data themselves indicate that the situation has been quite different in the past. While the computer models allow us to use the cosmogenic data to extend the cosmic ray record into the past, this does not, per se, provide information on the physical changes in the heliosphere in the past.

The theoretical understanding of the cosmic ray modulation processes obtained during the instrumental era provide us with a "Rosetta Stone" that allows us to decipher the paleo-cosmic ray records. The detailed data on the temporal changes in the cosmic ray intensity, spectrum, and anisotropy since ∼1960 have led to a good theoretical understanding of the modulation process, that allows us to investigate the solar and heliospheric properties throughout the previous 10,000 years.

The "cosmic ray propagation equation" of Parker [28] is the most important tool in investigating the cosmic ray modulation processes in the past. For example, using mathematical models based on that equation, Caballero Lopez et al. [29] have investigated the manner in which the heliomagnetic field, and turbulence therein, may have varied over the past 1000 years. Such studies involve hypotheses- the fact that the inferred temporal variations in magnetic field strength obtained using the ^{10}Be data is in good agreement with two independent estimates of the heliomagnetic field (based on the 150 year geomagnetic and the 400 year sunspot records) provides some confidence in the methodology and the assumptions [30]. Undoubtedly there will be further progress in this area; most probably stimulated by the need to understand the changing space weather and atmospheric circulation of the Earth.

On the basis of a number of simplifying assumptions, Gleeson and Axford [31] derived the "modulation potential" that relates the scattering properties of the heliomagnetic field, and the solar wind velocity, to the modulation observed at Earth and elsewhere in the solar system. This has been shown to be a useful approximation in study of the neutron monitor and satellite measurements over the past four decades, and provides a quasi-physical means to investigate the solar and heliospheric conditions in the past. It is used in this manner in the following section, and in the contemporary space weather community.

Long Term Changes in the Intensity of the Galactic Cosmic Radiation

Fig. 8 displays the intercalibrated cosmic ray data since 1428 [2], and major long term changes are clearly evident (see also [32] and [33]). It is clear that the cosmic ray intensity during the "instrumental era" has been one of the lowest in the past 1000 years. Since 850 AD there have been several ∼50 year periods of high cosmic ray intensity corresponding to the "Grand Minima" in the sunspot record, during which the 22-year average modulation potential has been as low as 100 MV.

Fig. 13 displays the ^{10}Be data from the "Spoerer Minimum"- the most profound "Grand Minimum" of solar activity in the past 1000 years. The ^{10}Be frequently approximates the LIS value throughout this period, yet it is clear that 11 and 22-year modulation was still present at this time of reduced solar activity (see also [34] for the Maunder Minimum). The high values ∼1460 will be discussed later.

The instrumental era has shown that the modulation process is strongly energy dependent. Fig. 14 displays the estimated cosmic ray spectra for the pre-instrumental era, implying that the low energy cosmic ray intensity at low energies has been a factor of ten and more greater than the present-day values in the recent past.

Fig. 10 displays the ^{10}Be and ^{14}C production rate for the past 10,000 years. The intensity increases at the time of the "Spoerer" and "Wolf" Minima of solar activity are on the left hand of

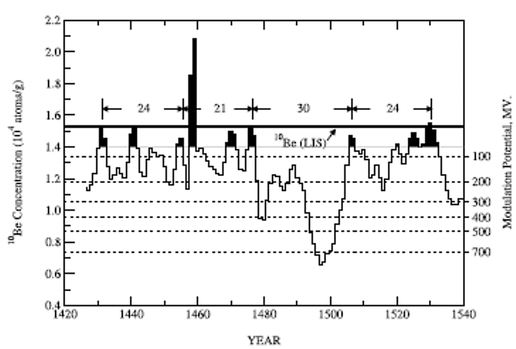

Fig. 13. The annual ^{10}Be data from Greenland during the Spoerer "Grand Minimum" in solar activity. The line labeled ^{10}Be(LIS) is the estimated ^{10}Be production when the local interstellar spectrum is incident on Earth [32].

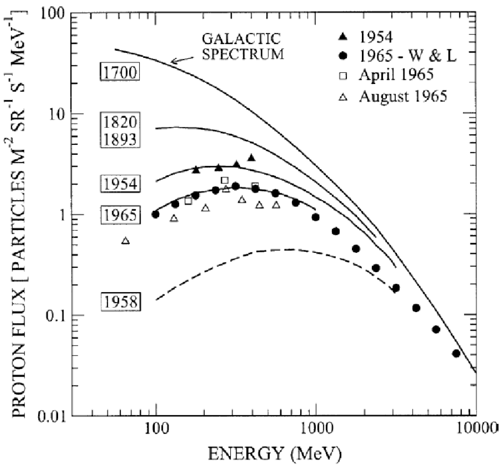

Fig. 14. The energy spectra of galactic protons observed by balloon and satellite instruments, and estimated using the ^{10}Be record [24].

the "Before Present" time scale. The figure shows that there were about 22 similar 50-100 year intervals of high intensity, amounting to about 18% of the previous 10,000 years. For the remaining 82% of the time the intensity was considerably lower, the lowest values approximating those of the present instrumental era. The long term changes are due to the changing magnetic moment of the Earth, having been high ∼2000 BP, and low 6000 BP. In summary, the intensity of the GCR changes markedly with time. It exhibited high values during the Maunder, and Spoerer "Grand Minima" of solar activity, and many other similar short lived periods of intensity have occurred in the past. It appears likely that the LIS was incident on Earth for portion of those times The intensity was at lower levels for the remaining 82% of the time; the present instrumental epoch is one such period.

Long-term Changes in the Solar Cosmic Radiation

Fig. 15 displays the occurrence of solar energetic particle (SEP) events in the interval 1890-1898 [23]. The five large events are all as large, or larger than the integrated SEP events of August, 1972; the event taken as the extreme event of the satellite era. That is, there were five high fluence events in five years 1895; while there was one in the 40 year duration of the space era. This shows

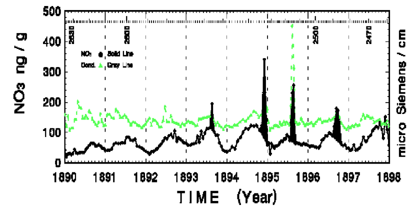

Fig. 15. The high time resolution nitrate record during the relatively low activity solar cycle 1890-1901 [11].

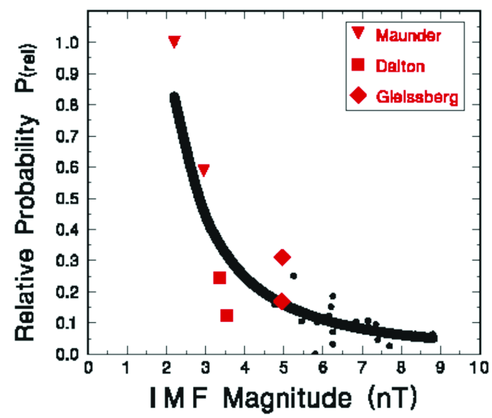

Fig. 16. The probability that a CME will produce an observable large-fluence SEP plotted against the estimated strength of the interplanetary magnetic field strength [35].

that there have been substantial long-term changes in the production of SEP events over the past 100 years. This appears counter-intuitive at first sight- the occurrence of high fluence SEP events being highest at the time of the smallest sunspot cycles. McCracken et al. [35] have examined this further by comparing the frequency of occurred of large SEP events, and the strength of the heliomagnetic field (Fig. 16). This shows a strong inverse dependence of the frequency of occurrence and the strength of the HMF. McCracken et al. [35], have proposed that this is a consequence of the strength of the solar fields being lower during small sunspot cycles, leading to lower Alfven velocities in the solar corona, and consequently, higher Alfven Mach numbers and more efficient particle acceleration. This concept has been developed in detail by Mann et al. [36].

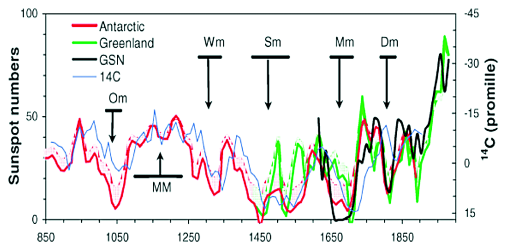

Fig. 17. The estimated sunspot number based on 10Be data from Antarctica, and Greenland, and from the ^{14}C record, compared to the observed sunspot number (GSN) [22].

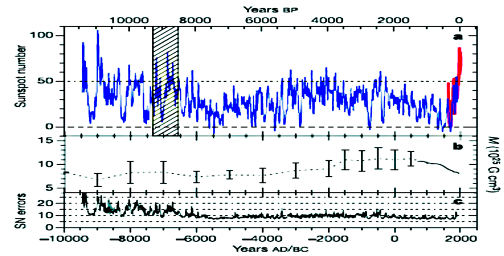

Fig. 18. The estimated sunspot number based on the ^{14}C record, after allowance for the changing geomagnetivc field [37].

Paleo-cosmic rays-implications and uses

As discussed here, the paleo-cosmic ray record extends much further into the past than the geomagnetic and sunspot records. It therefore provides a means to investigate the physics of galactic, solar, and magnetospheric processes in a more representative manner than when based on the present instrumental era, alone. Five examples are now discussed briefly to illustrate this new role of cosmic ray data.

Solar Physics

The ^{10}Be and ^{14}C data in Fig. 10 exhibit solar modulation effects superimposed upon changes due to the varying geomagnetic dipole moment. After calibration to the present epoch, and the removal of the geomagnetic effects, these data have been used to estimate the solar activity throughout the Holocene (to 11,000 BP). Figs. 17 and 18 are two such reconstructions ([22], [37]). These two reconstructions imply that the Sun is more active in the present epoch than at any time in the past ten millennia; other reconstructions suggest that it is one of the most active periods [21]. It is anticipated that the use of a number of ^{10}Be cores as well as the ^{14}C record will improve the long-term stability of these reconstructions, leading to a better understanding of solar activity over 1,000 solar cycles, and more.

Space Weather

The past 50 years have shown that satellites, various forms of infrastructure (air transport, railways, communications, navigation) and manned space flight are vulnerable to the occurrence of SEP events, and the prevailing level of the GCR intensity. The basic question is put; is the "space weather" observed during the "space era" a representative sample of the past, and the future. The paleo-cosmic ray data are one of the few sources of data that allows this question to be answered. As an example, let us compare the radiation conditions near Earth in 1900, with those during the space era. Using the ^{10}Be data to determine the modulation function as a function of time and using the SEP fluences inferred from the nitrate record we can estimate that:

- The GCR intensities at 100, 300, and 1000 MeV/nucleon were factors of seven, 3.5 and 2.25 greater in 1900 than during the present epoch (see Fig. 14), and
- The frequency of occurrence of large fluence SEP events was approximately five times greater near 1900 than in the space age.

Clearly, these are large differences, which may have considerable practical impact. It is therefore important that further data be obtained to validate these predictions. It appears possible that the ability to make these predictions may be a unique property of the cosmogenic record, and may assume great economic significance in the near future.

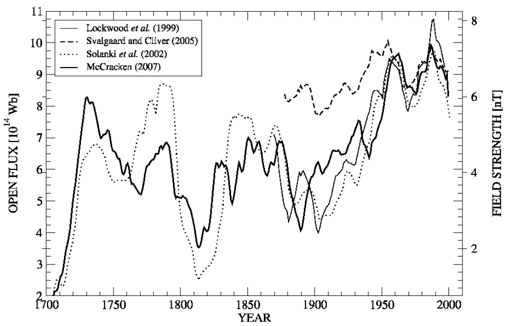

Fig. 19. Estimates of the strength of the interplanetary magnetic field near Earth. The heavy line [30] is based on the cosmogenic record and can be extended backwards throughout the Holocene, while no data exist to do so for the other three.

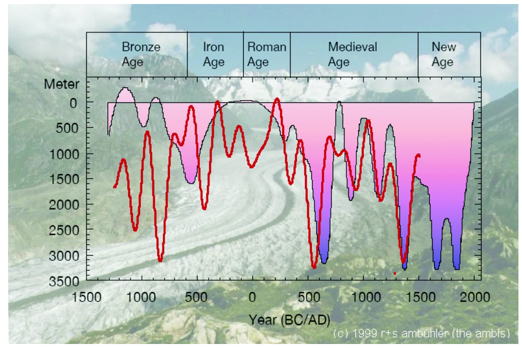

Fig. 20. The advance and retreat of the Aletsch glacier (Switzerland) estimated from ^{14}C dating of biological debris, compared to the cosmic ray modulation potential [Source J.Beer].

Heliopheric Physics

Fig. 18 presents estimates of the strength of the heliospheric magnetic field near the orbit of Earth based on geomagnetic, sunspot, and the paleo-cosmic ray record. Three of these independent estimates are in good agreement and this suggests that the paleo-cosmic ray record provides the means to estimate the temporal dependence of the heliomagnetic field in the past.

Astronomical Studies

Referring to Fig. 13, note the large increase in ^{10}Be concentration near 1460 AD. It was seen in other cores in both the Arctic and Antarctic, and exceeds the ^{10}Be concentrations attributable to the LIS in all cases. It is therefore unlikely to be due to modulation of the GCR; it is probably due to the injection of an additional source of ^{10}Be into the atmosphere. Two possibilities have been suggested; (1) that it is due to an extremely large SEP event that occurred during the Spoerer minimum of solar activity (no nitrate data exist for this period), or (2) that it is due to an intense gamma ray burst from the nearby supernova remnant, RJX0852.0 -4622, GROJ0852 -4622, [32]. This question remains unresolved, however it illustrates that the paleo-cosmic ray record may provide information on astronomical events that have occurred in the recent past.

Florinski et al. [38] have postulated that the cosmogenic data may be used to study the nature of the local interstellar medium in the recent past. Thus they argue that the dimension of the heliosphere will be affected by the properties of the interstellar medium, leading, in turn, to a variation in the cosmogenic record.

Terrestrial Climate

There is a clear coincidence between the high values of ^{10}Be concentration that accompanied the Spoerer, Maunder, and Dalton Grand Minima in solar activity, and the occurrence of the "little ice ages". Other studies have shown that the advance and retreat of the Aletsch glacier in Switzerland correlates well with low/ high values of the modulation potential derived from the paleo-cosmic ray record (Fig. 19). The cause of this correlation is presently unknown; both indirect and direct mechanisms have been proposed. In the indirect mechanism, a component of the solar irradience is a postulated to be a function of the strength of the solar (and sunspot) magnetic fields, which also determines the strength of the open heliomagnetic field, and thence the strength of the modulation of the cosmic radiation. One direct mechanism proposes that the cosmic rays themselves influence the albedo of the terrestrial atmosphere, thereby causing the Earth to be cooler when the GCR intensity is high. In view of the economic consequences of climate change, it is to be expected that there will be great continued interest in the use of the paleo-cosmic ray record in reaching a quantitative understanding of climate change.

Conclusions

The past decade has witnessed a revolution in our ability to use the cosmogenic record as a quantitative source of "paleo-cosmic ray" data that is inter-calibrated to the instrumental record that started in 1933. In all cases, large mathematical models have been the cause of this revolution. Of greatest importance, they have provided the specific yield functions for the cosmogenic nuclides, as well as the several instrumental cosmic ray detectors. In particular, this has led to the inter-calibration of the cosmogenic and instrumental records, allowing us to combine the several records to yield a single composite record stretching from 10,000 years in the past, to the present. In addition, a large atmospheric transport model has validated the use of the impulsive component of the nitrate in polar ice cores as a quantitative record of SEP events occurring in the past.

Computer intensive mathematical models have also allowed the production rate of ^{14}C to be determined from the observed data, and the mixing effects that determine the source of the ^{10}Be that is deposited in the polar caps. In so doing, sources of systematic and random error in the data have been minimized, and this process will continue in the future.

Based on these tools, and the inter-calibrated paleo-cosmic ray data, it has been shown that in the past 10,000 years the GCR has suffered 22 major modulation events similar to that accompanying the Maunder minimum at the end of the 17th century, and that the cosmic ray intensity has been anomalously low throughout the "space era". It has also been shown that SEP events appear to be more frequent during relatively weak sunspot cycles (e.g., circa 1900) compared to the present.

At present, our use of the cosmogenic record for cosmic ray studies is largely confined to the Holocene (the period after the last glacial epoch). An important challenge for the future is to develop the means to extent the calibrations, etc, back into the glacial epoch. Once this is done, the paleo-cosmic ray records will extend for 100,000 years into the past using ^{10}Be , and 40,000 years based on ^{14}C.

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