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The Annual Cosmic-Radiation Intensities 1391 – 2014; The Annual Heliospheric Magnetic Field Strengths 1391 – 1983, and Identification of Solar Cosmic-Ray Events in the Cosmogenic Record 1800 – 1983

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Abstract The annual cosmogenic ^{10}Be ice-core data from Dye 3 and the North Greenland Ice-core Project (NGRIP), and neutron-monitor data, 1951 – 2014, are combined to yield a record of the annual cosmic-ray intensity, 1391 – 2014. These data were then used to estimate the intensity of the heliospheric magnetic field (HMF), 1391 – 1983. All of these annual data are provided in the Electronic Supplementary Material. Analysis of these annual data shows that there were significant impulsive increases in ^{10}Be production in the year following the very large solar cosmic-ray events of 1942, 1949, and 1956. There was an additional enhancement that we attribute to six high-altitude nuclear explosions in 1962. All of these enhancements result in underestimates of the strength of the HMF. An identification process is defined, resulting in a total of seven impulsive ^{10}Be events in the interval 1800 – 1942 prior to the first detection of a solar cosmic-ray event using ionization chambers. Excision of the ^{10}Be impulsive enhancements yields a new estimate of the HMF, designated B(PCR-2). Five of the seven ^{10}Be enhancements prior to 1941 are well correlated with the occurrence of very great geomagnetic storms. It is shown that a solar cosmic-ray event similar to that of 25 July 1946, and occurring in the middle of the second or third year of the solar cycle, may merge with the initial decreasing phase of the 11-year cycle in cosmic-ray intensity and be unlikely to be detected in the ^{10}Be data. It is concluded that the occurrence rate for solar energetic-particle (SEP) events such as that on 23 February 1956 is about seven per century, and that there is an upper limit to the size of solar cosmic-ray events.

Keywords Cosmogenic ^{10}Be · Solar cosmic-ray modulation · Solar cosmic rays · Interplanetary magnetic field

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1. Introduction

The properties of the cosmogenic radionuclides, and their utilization for studies of solar activity in the past, have been described recently (Beer, McCracken, and von Steiger, 2012; McCracken *et al.*, 2013) and will not be repeated here. Recent studies have combined all of the available cosmogenic data for the past 9400 years, thereby extracting the solar signal from extraneous atmospheric and climate-related effects (Steinhilber *et al.*, 2012). That article used 22-year average data; in this article we use the two published sets of annual data that allow the study of shorter-term effects such as the Hale (22-year), Schwabe (11-year) and the short-lived solar energetic-particle (SEP) events associated with intense solar flares and coronal mass ejections (CME). Beer *et al.* (2011) have shown that the cosmogenic radionuclides (^{10}Be, ^{14}C, and ^{36}Cl, in particular) constitute the output of a "natural neutron monitor", providing a record of the intensity of the galactic cosmic radiation (GCR) far into the past. Accordingly, these radionuclides, singly, or in combination, provide measurements of the "paleo-cosmic radiation" (PCR), and we use that name herein.

The normalized data in Steinhilber *et al.* (2012) for the Spörer and Maunder Minima attained values in excess of the estimated value corresponding to the local interstellar spectrum (LIS). This is sometimes referred to as implying a negative value of the modulation function. Detailed analysis shows that the excessively high values were the consequence of three main factors: i) a measurement offset in the ice-core data from Dye 3 in Greenland; ii) a small uncertainty in normalization to the modern instrumental record, and iii) uncertainty regarding the energy dependence of the local interstellar cosmic-ray spectrum. The corrections for the first two factors will be detailed elsewhere but are summarized briefly in the following. In the case of the first factor, normalization of the cosmogenic data to the present epoch depended on the data from three ice cores: Dye 3 (Beer *et al.*, 1990), the "North Greenland Ice-core Project" (NGRIP, the data being given by Berggren *et al.*, 2009), and South Pole (Bard *et al.*, 1997), and close examination showed that the Dye 3 decrease in ^{10}Be concentration between 1900 and 1960 was substantially greater than those for NGRIP and South Pole. The contemporary atmospheric transport and mixing of the ^{10}Be prior to sequestration in the polar caps indicates that all three should be equal (Heikkila, Beer, and Feichter, 2009). We have used this equality to conclude that the concentrations observed at Dye 3 after 1900 were erroneously low. Applying a baseline correction removes the excessively high values of the Steinhilber 22-year averages during the Grand Minima (see below). That correction, together with a revised normalization to the instrumental epoch, has removed most of the "negative" values of the modulation function. The revised 22-year data and the estimates of the modulation potential will be published elsewhere.

Before proceeding to discuss the annual data, we summarize certain important features of the cosmogenic ^{10}Be records:

- Unlike the modern neutron monitor (NM), the standard deviation is large ($\approx$20 %) for the annual ^{10}Be data from a single ice core.
- The cosmogenic data have an energy sensitivity broadly similar to, but peaking at lower energies than, a high-latitude (*i.e*, polar) sea-level NM (peaking at 0.9 – 1.5 GeV nucleon^{-1} compared to 4.5 GeV nucleon^{-1}, respectively – see Figure 6.5-2 of Beer, McCracken, and von Steiger, 2012). As a consequence, the time-dependent variations are larger; thus the Schwabe cycle has a typical amplitude of $\approx$40 – 45 % in the ^{10}Be data compared to 15 – 20 % for the NM.
- There is a delay of one to two years before the ^{10}Be is sequestered in the polar regions. The delay is shortest (days to weeks) for nuclides generated in the troposphere; it is much longer for production in the stratosphere (one to four years). The majority (65 %) of the

^{10}Be is produced in the stratosphere (Chapter 13 in Beer, McCracken, and von Steiger, 2012).
- The "Grand Minima" that we will discuss are intervals of duration from 40 – 120 years during which solar activity was very low: there have been ≈26 in the past 10,000 years. In this article we refer to the three most recent: the Spörer (1415 – 1530), the Maunder (1645 – 1715), and the Dalton (1790 – 1830) Minima.

To aid understanding, Electronic Supplementary Material Table S2 summarizes the more uncommon acronyms used in this article.

2. The Annual Paleo-Cosmic Ray Data and the Pseudo-Neutron Monitor Record

We have used the two extended annual data sets that are available at present; they are from Dye 3 in Greenland (65.18°N, 43.83°W, 2480 m a.s.l.; Beer *et al.*, 1990) and North GRIP (75.10°N, 42.32°W, 2917 m a.s.l. (Berggren *et al.*, 2009). Those data have been processed as described in Appendix 1. Briefly, the following steps were taken:

- computation of the averages for each year,
- compensation for the small baseline offset of the Dye 3 data outlined in the Introduction,
- using the 22-year record obtained by Steinhilber *et al.* (2012) to remove the long-term variations of atmospheric origin,
- correction for the 6.5 % decrease in the geomagnetic dipole moment between 1391 and the present,
- computation of $Y_{\text{stein,GM}}(t)$, the annual ^{10}Be concentration relative to the average for the reference interval 1945 – 1985 used by Steinhilber *et al.* (2012),
- estimation of $Y_{\text{LIS,GM}}(t)$, the observed concentration of ^{10}Be expressed relative to that which would be observed if the local interstellar cosmic-ray spectrum were incident on Earth. The latter data were used in the subsequent computations in this article.

The neutron monitor provides one of the most important instrumental records of the intensity of the cosmic radiation near Earth. The record commenced in 1951, and since 1957 there have always been >50 instruments in the world-wide network. Initially following the International Geophysical Year (1957) specification, the first instruments are often referred to as IGY neutron monitors. A larger, more sensitive version was specified for the International Quiet Sun Year (1964); commonly called the "super" NM. The increased statistical accuracy of the IQSY version is the primary difference between the two versions, and nearly all of the IGY NM have been replaced by super NM; henceforth we will refer to both versions collectively as neutron monitors (NM). They have provided a great deal of our understanding of the temporal, energy, and directional dependence of the >1 GeV nucleon^{-1} cosmic radiation near Earth. The ^{10}Be data can be regarded as the output of a natural neutron monitor (Beer *et al.*, 2011), and it is convenient to use them to estimate the NM counting rate that would have been observed in the past. Using the procedure described by McCracken and Beer (2007), $Y_{\text{LIS,GM}}(t)$ defined above was used to compute the annual pseudo-neutron-monitor counting rate [PNM(t)], for a high-latitude sea-level NM; see further details and Figure 6 in Appendix 2. Oh *et al.* (2013) have made a detailed examination of the data obtained by 15 NMs since 1964, and have published a composite record for 1965 – 2013 based on eight high-latitude sea-level NMs. We have normalized the PNM estimates to that record, where the peak counting rate observed during the sunspot minimum of 1987 is assigned the value of 100 %.

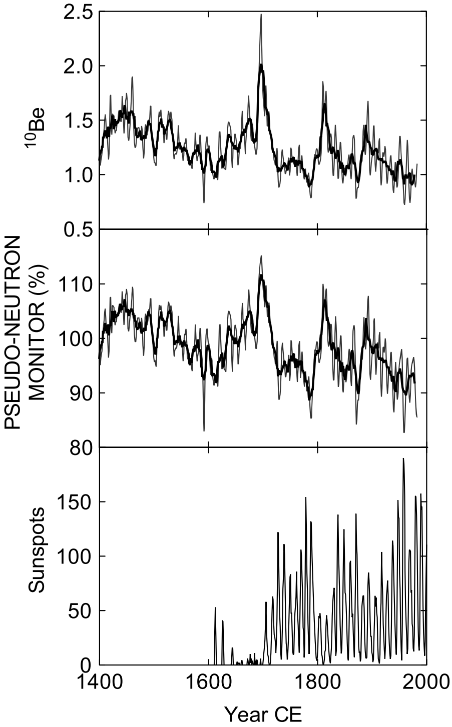

Figure 1 The variable nature of the cosmic radiation at Earth in the interval 1400 – 2000. All of the data represented by the thin lines in the top two panels have been passed through a (1,4,6,4,1) binomial filter (see Appendix 1). The thick lines denote the 11-year running averages of the annual data. (a) The concentration of ^{10}Be relative to the average for 1944 – 1987 used by Steinhilber *et al.* (2012); (b) the pseudo-neutron-monitor record relative to the sea-level, high-latitude NM counting rate for February 1987, and (c) the smoothed international sunspot number. The annual values corresponding to the data in panels a and b are given in Table S1 of the Electronic Supplementary Material.

Figure 1 displays the annual ^{10}Be data [$Y_{\mathrm{stein,GM}}(t)$], the pseudo-neutron-monitor data [PNM(t)], and the smoothed international sunspot number (also see Electronic Supplementary Material Table S1). This shows that the cosmic-ray intensities during the modern instrumental era are substantially lower than those during the Spörer, Maunder, and Dalton Grand Minima (for further discussion see McCracken and Beer, 2014). The relationship between the ^{10}Be data and the NM counting rate is substantially non-linear (Figure 5, McCracken and Beer, 2007). This is the consequence of two factors: i) the ^{10}Be response extending to lower energies, and ii) the amplitude of the modulation increasing rapidly towards lower energies. For example, the ratio between the percentage changes in the ^{10}Be data and the sea-level, high-latitude NM counting rate is 1.45 throughout the instrumental era (1951), while it increases to 4.4 during the Grand Minima such as the Maunder Minimum (1645 – 1715). This results in the differences that are evident for the highest cosmic-ray intensities in the top two panels of Figure 1.

3. Annual Estimates of the Heliospheric Magnetic Field and the Presence of Solar Cosmic-Rays in the Cosmogenic Record

The cosmic radiation reaching the Earth must traverse the heliomagnetic field from the heliopause (at 120 AU) to Earth (1 AU). The strength and configuration of that field therefore determines the intensity of the cosmic radiation reaching Earth (Potgieter, 2013). That is, the PCR record provides the output of a "cosmic magnetometer". Using a three-dimensional model of the heliosphere that included a solar-cycle-dependent current sheet, latitude-dependent solar-wind velocities, and the Hale cycle of solar magnetic fields, Caballero-

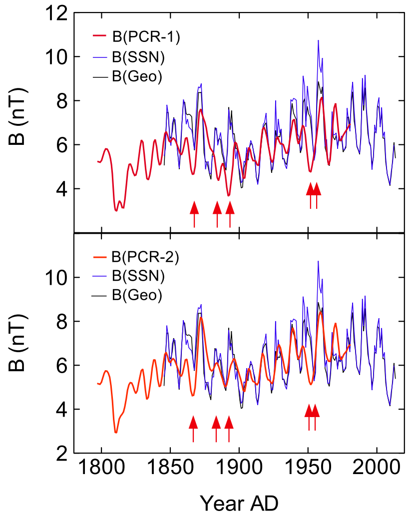

Figure 2 Comparison of the heliospheric magnetic field near Earth derived from geomagnetic data, sunspot number, and paleo-cosmic-ray data. Blue lines – B(SSN) derived from sunspot records; black – B(Geo) derived from the geomagnetic record. Heavy red lines; Upper panel, B(PCR-1) derived from the ^{10}Be concentrations given in the upper panel of Figure 1; Lower Panel; B(PCR-2) derived from the ^{10}Be concentrations after removal of the ^{10}Be generated by solar cosmic radiation. All data have been passed through a (1,4,6,4,1) binomial filter (see Appendix 1). The red arrows indicate occasions when the ^{10}Be concentrations were higher at sunspot maximum than at sunspot minimum. See text for further details of all the above.

Lopez *et al.* (2004) developed the means to use the PCR record to estimate the heliospheric magnetic-field (HMF) intensity near Earth. Henceforth, we refer to this as B(PCR). McCracken (2007a) modified that method, using the NM record to calibrate the inversion process to the satellite observations of HMF intensity since 1965. An outline of the method used in this article is given in Appendix 3. In brief, using a look-up table, the observed ^{10}Be data are used to estimate the time-dependent diffusion coefficient $k(t)$ of the GCR in the heliosphere at time t in the past. Using those, and calibrating to the near Earth HMF observed during the satellite era, Equation (1) is used to estimate B(PCR) as a function of time in the past.

The Caballero-Lopez *et al.* method applies to values of $^{10}\mathrm{Be}(t)_{\mathrm{av}}/^{10}\mathrm{Be}(\mathrm{LIS}) < 0.8$. Equation (1) shows that this corresponds to $B(\mathrm{PCR}) > 2.5$ nT, and consequently upper limits of 2.5 nT are given for $^{10}\mathrm{Be}(t)_{\mathrm{av}}/^{10}\mathrm{Be}(\mathrm{LIS}) > 0.8$. Such years were rare: four occurred in the Spörer Minimum (1420, 1421, 1442.1, and 1460.1), six in the Maunder Minimum between 1692.7 and 1698.7, and two in the Dalton Minimum (1810 and 1811). Note that decimal years are used before 1775, as discussed in the description of column 1 in the Electronic Supplementary Material.

Using the method outlined above, Figure 2 displays two different estimates of the HMF, B(PCR-1) and B(PCR-2), for the interval 1800 – 2010. Considering first the top panel, B(PCR-1) was derived using $Y_{\mathrm{LIS,GM}}(t)$ as discussed above. Independent estimates of the heliospheric magnetic field have been obtained using the sunspot and geomagnetic records (B(SSN) and B(Geo), respectively) and are also given in Figure 2 (Lockwood *et al.*, 2013; Svalgaard, 2014). In general, there is reasonable agreement between the Schwabe cycles, and the long-term changes associated with the Dalton and Gleissberg "Grand Minima". However, there are five striking differences indicated in the figure: the very low values of

B(PCR-1) in 1858 – 1865; 1884 – 1886; 1892 – 1894; 1947 – 1952 and 1957, all in proximity to sunspot maxima.

The annual NM record from 1951 to the present (Oh *et al.*, 2013; McCracken and Beer, 2014) shows that the cosmic-ray intensity decreases rapidly below the sunspot minimum value at the commencement of a Schwabe cycle. In a similar manner, for the majority of the solar cycles in the PCR record, the annual ^{10}Be production rate has decreased by > 40 % in the three to four years between sunspot minimum and maximum. Examination of the top panels of Figures 1 and 2, and Table S1, shows that the five low estimates of the HMF are the consequence of the ^{10}Be concentrations being substantially higher at sunspot maximum than at the preceding sunspot minimum. This is totally inexplicable in terms of the modulation of the GCR by the solar wind and its entrained magnetic field.

The instrumental measurements of the cosmic radiation made using ionization chambers and neutron monitors have shown that there are occasional very intense bursts of cosmic rays associated with solar flares, and/or the occurrence of coronal mass ejections. Based on their best estimates of the energy spectra of these events, Webber, Higbie, and McCracken (2007) have shown that some of these events might be detectable in annual ^{10}Be data. Usoskin *et al.* (2006) have reported ^{10}Be enhancements that they attribute to solar cosmic rays. Compared to these earlier studies, we now have the advantage of two totally independent records of high-resolution ^{10}Be data. We now use them to consider the possibility that the low estimates for B(PCR-1) in Figure 2 are the consequence of the production of ^{10}Be by solar cosmic rays. (Detailed records of the instrumental observations of solar cosmic-rays are given at usuarios.geophysica.unam.mx/GLE_Data_Base/files/. A summary listing of all ground-level events (GLEs) with NM enhancements > 10 % is given by McCracken, Moraal, and Shea, 2012.)

4. Evidence for Solar Cosmic-Ray Events in the ^{10}Be Data and Their Influence on B(PCR-1)

Examination of the annual PCR data demonstrated that there were significant (30 – 60 %) single-year enhancements in the PCR in the year following the very large solar cosmic-ray events of 1942, 1949 (Forbush, 1946; Forbush, Stinchcomb, and Schein, 1950), and 1956 (Meyer, Parker, and Simpson, 1956). These impulsive enhancements will masquerade as reductions in the strength of the HMF; calculations as outlined in Section 3 show that these solar cosmic rays would be interpreted as ≈ 2 nT to 3 nT decreases in the estimated HMF for each single-year enhancement. A screening criterion was developed to identify large impulsive ^{10}Be events in the data from Dye 3 and North GRIP. Using annual data, this criterion required that: i) there was a three-standard-deviation single-year (or rarely two- or three-year) increment in the averaged data from the two cores; ii) there was at least a one-standard-deviation increase in each core. Eleven impulsive events, comprising 16 annual enhancements, were identified by this process in the interval 1800 – 1983 and are listed in Table 1.

To validate these observations, and the association with solar cosmic-ray events, the annual ^{10}Be data were processed through a running (1,4,6,4,1) binomial filter (see Equation (1) in Appendix 1) and the year-by-year output subtracted from the annual data, thereby removing the 11-year and longer-term variations in the data. The residuals from this process are displayed in Figures 3 and 4. The former is for the interval 1800 – 1983 considered in Figure 2, for which there are geomagnetic and sunspot-based estimates of the HMF as discussed previously (Lockwood *et al.*, 2013; Svalgaard, 2014). Figure 4 displays the period

Table 1 Impulsive enhancements in the ^{10}Be record. In the following "wrt" is an abbreviation for "with respect to". Columns 1 and 2, year and amplitude (in % of mean) of impulsive event; Column 3, above line – date of known solar cosmic-ray ground-level event (GLE); below line – known Great Geomagnetic Storm (GMS); Column 4, Delay between GLE (GM Storm) and impulsive ^{10}Be event [months]; Column 5, period between sunspot minimum and event [years]; Column 6 > 4 GeV fluence of GLE in percent relative to 23 February, 1956 (McCracken, 2007b). Bold entries in columns 1 and 2 were identified by the screening criterion given in the text. Italics indicate two > 2-standard-deviation impulsive events possibly associated with well-known GLEs as discussed in the text. The asterisks in column 3 refer to the footnotes.

^{10}Be Impulse Date	Amp. ^{10}Be	GLE/GMS date	Delay wrt SEP	Delay wrt SSmin	GLE Fluence
1974	*17*	*Sep. 1972*	*16*	*9.5*	*<10*
1965	**82**	Nuclear tests	29	0.2	
1963	*18*	*Nov. 1960*	*25*	*8.2*	*<10*
1957	**53**	Feb. 1956	10	2.7	100
1951	**29**	Nov. 1949	13	6.8	98
		Jul. 1946		2.3	70
1943	**30**	Feb. 1942	10	9.3	80
1938	**43**	24 Apr. 37*	8	4.0	
1930	**36**	8 Jul. 28	17	**5.0**	
1903	**32**			**0.9**	
1892 – 1894	**76**	multiple*		1.8	
	47			2.8	
	60	multiple*		3.8	
1884 – 1885	**47**	17 Nov. 82*	13	**5.0**	
	64	multiple*		**6.0**	
1873	**42**	4 Feb. 72*	10	5.0	
1816	**39**	high SSN*	9	5.5	

1937, 38: 3 and 5 "Great Storms", respectively.

1892 and 1894: 9 and 8 "Great Storms", respectively.

1882, 83: 5 and 2 "Great Storms", respectively.

1870, 71, 72: 6, 6, and 5 "Great Storms", respectively.

1815: February – June 1815 – rapid rise in sunspot number to 59.

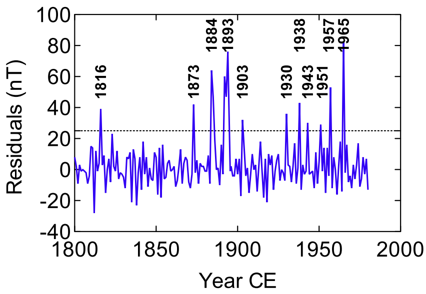

Figure 3 The residuals obtained by subtraction of the 11-year (Schwabe) and longer-term modulation from the annual ^{10}Be (see Section 4). The dates of the impulsive enhancements are given. Enhancement amplitudes are given in percent of the annual mean. The dotted line indicates the three-standard-deviation limit of the residual population.

for which there is an instrumental record of the galactic cosmic radiation (GCR). The 11 impulsive events in Figure 3 labeled with dates are in one-to-one agreement with those in Table 1 that were identified by the initial screening process. They were then excised from the ^{10}Be record, leaving 167 residuals whose standard deviation was computed to be 8.5 %.

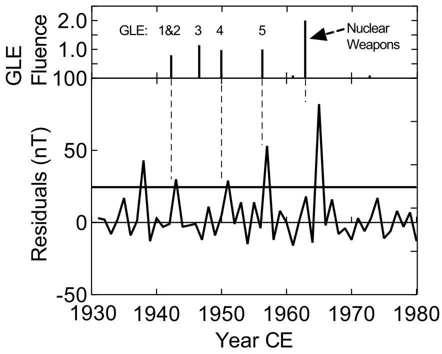

Figure 4 The relationships between the observed "Ground Level Events" observed following the production of cosmic rays by the Sun, and the impulsive increases in the ^{10}Be record. The thick-black-horizontal line indicates the three-standard-deviation limit of the residual population as described in Section 4. The intervals between the GLE and the nuclear events, and the subsequent ^{10}Be events are (from left to right) 10, 13, 10, and 25 months, and they are consistent with the known one- to two-year delay between the production of ^{10}Be in the stratosphere and sequestration in polar ice.

This is consistent with the expected experimental and system (*e.g.* atmospheric effects) uncertainties in this relatively short data record. The horizontal lines in Figures 3 and 4 are three standard deviations above the mean and all 11 impulsive events identified by the initial screening process exceed that line.

Before we proceed, it is important to note an important difference between the instrumental and cosmogenic records of solar cosmic rays. A cosmic-ray instrument (ionization-chamber, or NM) records the instantaneous cosmic-ray flux $[\int j(t) S_i(E)\,\mathrm{d}E]$ as a function of time throughout the event (where $j(E,t)$ is the differential energy spectrum of the solar cosmic rays and $S_i(E)$ is the specific-yield function of the instrument (see Equation 6.5-1 of Beer, McCracken, and von Steiger, 2012)). In the literature, GLEs are frequently ranked according to the peak flux attained during the events. By way of contrast, the ^{10}Be production during a solar event (and sequestered in polar ice) is given by the time integral $\iint j(t,E) S_c(E)\,\mathrm{d}E\,\mathrm{d}t$ for the duration of the event. Writing $\int j(t,E)\,\mathrm{d}t = F(E)$, the differential fluence of the event at energy E, then the ^{10}Be production $= \int F(E).S_c(E)\,\mathrm{d}E$, where $S_c(E)$ is the specific-yield function for the production of ^{10}Be. The time scale of solar cosmic-ray events is a highly variable quantity, varying by a factor as great as 36 from event to event (McCracken and Palmeira, 1960). As a consequence, a GLE with a relatively small peak flux may have a fluence similar to one with a high flux. For example (as discussed further in Section 7), the GLE of 25 July 1946, with a peak ionization-chamber flux $\approx 16\ \%$ of that of 23 February 1956, but a time scale ≈ 4.25 times greater, had a fluence 0.7 times that of the latter for the energies responsible for ^{10}Be production. Consequently that GLE, while relatively small in terms of peak flux, is estimated to have resulted in an increase in ^{10}Be production similar to that of the "very large" GLE of 23 February 1956. Recognizing this, column 6 of Table 1 lists the > 4 GeV fluencies of all of the solar cosmic-ray events adapted from McCracken (2007b).

Table 1 summarizes the properties of the 11 impulsive events identified by both the selection process and as three standard deviation events in Figure 3. The portion of Table 1 above the dotted line corresponds to the interval for which there is an instrumental cosmic-ray record (ionization chambers 1937 – 1960; neutron monitors from 1951; satellites from 1960). Below the line, associations with major geomagnetic storms are noted, and these will be discussed in Section 6.

We now use Figure 4 to investigate the association of the impulsive ^{10}Be enhancements with the known solar cosmic-ray events. The upper graph gives the times of occurrence and > 4 GeV fluence of the largest cosmic-ray events in the ionization-chamber and neutron-monitor records (see also Table 1). By convention, GLEs are numbered in sequential order; thus GLE5 is the event of 23 February 1956, being the fifth event recorded by ground-level instruments (Meyer, Parker, and Simpson, 1956). In terms of peak flux, it was the largest ground-level event (GLE) in the neutron-monitor record, and it preceded a 53 % single-year enhancement in the ^{10}Be data in the following year. In a similar manner, the ^{10}Be enhancements in 1942 and 1951 were in the years that commenced 10 and 13 months after GLE 1 and 2 (February/March 1942), and GLE 4 (November 1949). These delays are consistent with the $\geq$ one year required for ^{10}Be produced in the stratosphere to be sequestered in polar ice. This and the Webber, Higbie, and McCracken (2007) predicted production rates support the proposed association of the impulsive ^{10}Be enhancements with very large solar cosmic-ray events.

The instrumental cosmic-ray record shows that a single sunspot group may result in more than one GLE over a period of a week or more (*e.g.* 28 February and 2 March 1942; 12, 15, and 20 November, 1960). There may be many GLEs in a single Schwabe cycle (*e.g.* seven GLEs were observed during Schwabe Cycle 19 (1954 – 1965)). The annual ^{10}Be data precludes the identification of multiple events within a year; we therefore associate an annual ^{10}Be enhancement with a "solar cosmic-ray episode". Depending on the level of solar activity, the instrumental record shows that there may be more than one year with such an episode in a Schwabe Cycle, and that they may be contiguous.

Examining Figure 4 and Table 1 we note that:

- Five relatively small (< 300 %) GLEs were observed by neutron monitors in the interval May – November 1960; in total, their NM response approximated 25 % of that of the GLE of 23 February 1956. Solar events in August 1972 resulted in two small GLEs, while the particle fluence observed by satellite-borne detectors was the greatest observed up to 1980 (Smart, Shea, and McCracken, 2006). While they were too small to be identified by our screening process, the two standard deviation ^{10}Be enhancements in 1963 and 1974 in Figures 3 and 4 are consistent with their being produced by these two well-known episodes of production of cosmic rays by the Sun. For this reason, they are included in Table S1 (Electronic Supplementary Material).
- The ^{10}Be enhancement of 1965 is the largest in Table 1, and occurred within two months of solar minimum, making a solar origin unlikely. It commenced approximately two years after the detonation of six nuclear weapons at high altitudes in the interval July to November 1962. Three of these, Starfish, Bluegill, and Kingfish, were detonated by the USA at altitudes of 400, 50, and 97 km, respectively, with a total yield of nine PJ (2.2 megatonnes). The Soviet Union detonated three weapons with an estimated total yield of 0.9 megatonnes in the altitude range 59 – 290 km. These detonations have resulted in intense neutron irradiation of the upper stratosphere, leading to the production of ^{10}Be in an analogous process to the production of cosmogenic ^{10}Be. The neutron and proton fluxes due to cosmic rays are not fully developed until an atmospheric depth of 100 $\mathrm{g\,cm^{-2}}$ is reached (Chapters 10 and 13, Beer, McCracken, and von Steiger, 2012) and consequently the production of ^{10}Be by cosmic rays is most efficient in the lower stratosphere and troposphere. In the case of the nuclear weapons, the full neutron intensity will have extended throughout the stratosphere. The sequestration of ^{10}Be in the polar caps takes from one year in the lower stratosphere, to up to four years in the upper stratosphere (Section 13.2 of Beer, McCracken, and von Steiger, 2012), and the observed delay of approximately

two years is therefore consistent with the ^{10}Be enhancement of 1965 being a consequence of the high-altitude nuclear tests in the latter half of 1962.

– There is no record of a solar cosmic-ray event prior to the impulsive ^{10}Be enhancement of 1938. There was a major Forbush decrease in April 1937, however, no solar cosmic-ray event was reported at that time. The Christchurch and Cheltenham ionization chambers had only been in operation for 12 and 1 month, respectively, in April 1937, providing little experience regarding the fluctuations in the galactic cosmic radiation. Scott Forbush described (personal communication to KGMcC, *circa* 1965) the administrative opposition he faced in 1946 when seeking to publish his discovery article of the solar cosmic-ray effect (Forbush, 1946). The opposition from his supervisor was that "there are no known physical processes on the Sun that would lead to acceleration of protons to these energies and therefore the enhancements must be due to faulty instruments". We may speculate that the same opposition was present ten years earlier, and without the benefit of a good understanding of the temporal variability of the galactic cosmic radiation and the stability of the instruments that had been developed by 1946, Forbush may have deemed it advisable in 1937 to accept the possibility that it was an instrumental effect. Copies of the original records still exist, and it will be instructive to reinterpret them in the light of subsequent experience.

– While all the other known GLE in Table 1 and Figure 4 can be associated with ^{10}Be enhancements, this is not so for the large, long duration solar event of 25 July 1946. This will be discussed in more detail later where we suggest that a ^{10}Be enhancement may escape detection if it coincides with the rapidly decreasing initial phase of the 11-year cosmic-ray modulation.

In summary, the annual screening process, and the residuals obtained after subtraction of the underlying 11-year modulation provide consistent identification of impulsive ^{10}Be enhancements that are greater than three times the standard deviation of the experimental and statistical noise. Furthermore, for the period for which instrumental data are available, the amplitude and delay properties of five of the six ^{10}Be enhancements are quantitatively consistent with production by solar cosmic rays. We conclude that the impulsive ^{10}Be enhancements are primarily associated with the occurrence of one or more large SEP with substantial fluxes > 1.0 GeV. Nevertheless there are errors of omission and commission; the former such as illustrated by the GLE event of July 1946; the latter by the putative "Nuclear Weapon Tests" event of 1962.

5. Definition of the B(PCR-2) Estimate of the HMF

Based on the above result, both selection criteria were applied to the data from both cores for the interval 1775 – 1983 (limited to the interval for which annual estimates have been made using a cubic-spline interpolation). The 13 enhancements were excised from the annual data and replaced by the average of the adjacent values. This modified time series was then inverted (as outlined in Section 3), yielding the second estimate B(PCR-2) plotted in Figure 2. Examination of that figure shows that B(PCR-2) does not contain the low values of B(PCR-1) that coincided with the sunspot maxima of 1883 and 1893 and the GLE of 23 February 1956. However, we note that the low value *circa* 1950 is only partially reduced, and that *circa* 1860 is not reduced at all. These will be discussed further in Section 7. The annual values of B(PCR-2) are given in the Electronic Supplementary Material, Table S1, for the interval 1775 – 1983. They will be compared with the geomagnetic and sunspot-based estimates [B(GEO) and B(SSN)] in a forthcoming article (Owens *et al.*, 2015).

6. Impulsive ^{10}Be Events Prior to 1942

As discussed above, five of the six ^{10}Be enhancements above the dotted line in Table 1 are closely associated with known solar cosmic-ray events. We now consider briefly the ^{10}Be enhancements prior to 1942. Examination of the historical record shows that very great geomagnetic and auroral activity occurred on the dates given in Column 3 of Table 1. The time delays to the commencement of the ^{10}Be impulsive events are given in column 4 and are all consistent with the one to two year sequestration time for ^{10}Be as discussed previously. The Greenwich list of Great Magnetic Storms (Jones, 1955) shows that the intervals immediately prior to many of the ^{10}Be enhancements contained a high number of "Great" storms, as listed in the footnote to Table 1. We conclude that the ^{10}Be enhancements prior to 1942 are consistent with being produced by solar cosmic rays generated by the CMEs associated with one or more "Great" magnetic storms. In the case of the enhancement in 1816, there was a rapid rise in sunspot activity to a monthly sunspot number of 58.8 between February and June 1815. This could indicate the occurrence of a CME yielding a SEP event with an appropriate time lag to the observed ^{10}Be enhancement the following year. We note that three of the very large GLEs in the modern era (GLE 1, 69, and 70) occurred when the monthly sunspot numbers were 52.8, 31.3, and 13.6, respectively, demonstrating that large GLEs can occur at times of relatively low sunspot number (thus, 1816 was in the Dalton "Grand Minimum" of solar activity).

We note that the 1816 and 1884 – 1985 ^{10}Be enhancements occurred immediately after the occurrence of two of the largest volcanoes on record, Tambora (10 August 1815, 8°S; 118°E) and Krakatoa (27 August 1883; 6°S; 105°E). Volcanic ejecta do not contain ^{10}Be, however, the SO_2 and aerosols might modify the sequestration of the ^{10}Be produced by the GCR. There would be no net change in the quantity of ^{10}Be produced, and an enhancement in one year would imply a reduction in subsequent years. Such a reduction is not seen; and the good correlation with solar cosmic-ray events since 1942 suggests that the majority of ^{10}Be enhancements are of solar origin, with the possibility of a minor effect associated with atmospheric processes initiated by large volcanoes.

7. The Non-detection of the GLE of 25 July 1946 (GLE3)

Table 1 shows that the selection criteria identified seven impulsive enhancements (totaling ten years of enhanced ^{10}Be production) prior to the first GLE events observed by ionization chambers in 1942. Before we discuss them, however, we consider the large GLE of 25 July 1946 that was not identified in the ^{10}Be data by the selection criterion. Comparing the isotropic phases of the events as seen by ionization chambers (Smart and Shea, 1991), the flux amplitude of GLE3 was ≈ 16 % of that of GLE5 (23 February 1956). However, it was a factor of 4.25 longer duration (McCracken and Palmeira, 1960). Based on that, the > 4 GeV fluence is estimated to be a factor of $\approx 0.16 \times 4.25 = 0.7$ times that of the event of 23 February 1956, as given in Table 1. We conclude that this GLE will have produced a quantity of ^{10}Be similar to the GLE of 23 February 1956, thereby resulting in a reduction in the annual value of B(PCR) ≈ 3 nT. We now consider the superposition of such injections of ^{10}Be upon the 11-year cycle of galactic cosmic-ray intensity to understand the circumstances under which they will not be recognized by our selection criterion, or be visible in Figure 4.

Figure 5 plots the estimated ^{10}Be production rate for the two solar cycles 1944 – 1965, based on the estimates for the Climax NM derived from ground-level and high-altitude ionization-chamber data (Table 2 of McCracken and Beer, 2007). In common with all of

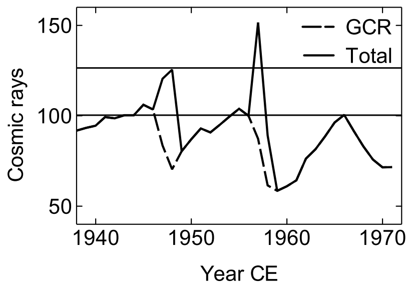

Figure 5 The phasing effects that occur in the superposition of a solar cosmic-ray event on the 11-year variation of the GCR in the cosmogenic record. The same intensity solar event was applied on 25 July 1946 and 23 February 1956. The upper horizontal line represents the three-standard-deviation selection criterion used in this article. The 1946 event would not be recognized using this criterion, while the 1956 event would.

the solar cycles in the NM, satellite, and cosmogenic records, the GCR intensity reached a minimum within three to four years, and then recovered to the sunspot minimum value over the following seven to eight years. For illustrative purposes, assume ^{10}Be production equal to 60 % of the annual rate for both the July 1946 and the February 1956 GLE. The former GLE occurred when the estimated ^{10}Be production rate due to the GCR had already decreased by $\approx$35 %, and it was mid-way through the year, so sequestration of the ^{10}Be would have been spread over the following two years, 1947 – 1948 and 1948 – 1949. The February 1956 GLE occurred when the estimated ^{10}Be production rate had only decreased by $\approx$10 % and early in the year, so the majority of the ^{10}Be would have been sequestered in the following year, 1957 – 1958. Figure 5 shows that in the former case the 60 % event would only result in a $\approx$23 % enhancement above the solar minimum value, and this would not be detected by the selection criteria. In the latter case (February 1956) the higher GCR intensity and occurrence earlier in the year means that the 60 % event would be detected. In summary, a solar event similar to that of 23 February 1956 would not be identified if it occurred late in the second or third year of the solar cycle. It would, however, result in a $\approx$3 nT under-estimate in the HMF, as illustrated by the low estimate for 1947 in Figure 2.

8. The Large Solar Cosmic Ray Events in the Cosmogenic Record, 1800 – 1942

Table 1 lists a total of ten impulsive ^{10}Be episodes (comprising 13 years of enhanced ^{10}Be) in the 180-year interval 1800 – 1980 that are broadly comparable to solar cosmic-ray production (sometimes in more than one event) in the GLE of 23 February 1956. Allowing for the failure to identify events for the onset phase of the solar cycle, we estimate that large solar events have occurred near Earth with a frequency of approximately seven per century. We note that none of the events were significantly greater than that of 23 February 1956, lending support to the proposal that there is a limiting size for solar events (Schrijver *et al.*, 2012).

9. Looking to the Future

We have shown that an annual ^{10}Be record provides the means to study the cosmic-ray intensity, the heliospheric magnetic field, the occurrence of large solar cosmic-ray events, and the overall level of solar activity far into the past. This will lead to a better understanding of the space weather in the past, thereby providing the means for a more comprehensive prediction capability in the future. In addition, improved definition of the 11-year cycles of cosmic-ray intensity would allow determination of the cosmic-ray drift characteristics (Potgieter, 2013). This will provide the only known way to determine the polarity of the solar dipole in the past. To these ends the following initiatives would be appropriate and would result in: i) sharper definition of the solar cycles in the past; ii) improved detection of solar cosmic-ray events in the past; iii) better understanding of the solar dynamo, and iv) improved accuracy of the estimates of the HMF, B(PCR):

i) Increasing the number of annual ^{10}Be records to a total of about five, with two of the new ones coming from the Antarctic. The overall goal would be a reduction in statistical and system noise, and minimization of the long-term synodic changes that they introduce into long-term comparisons. Five independent sets of data would yield a standard deviation of ≈ 5.5 % for the annual paleo-cosmic-ray data; 0.3 nT for the estimates of the heliospheric magnetic field near Earth, and allow solar cosmic-ray events such as the combined effect of the five relatively small events during 1960 to be detected as three-standard-deviation impulsive ^{10}Be events.
ii) Extending the annual PCR record back to 1000 BP (950 CE) to provide the ability to study the solar, cosmic-radiation, and magnetic-field effects with annual resolution through the whole cycle of Grand Minima from the Oort (≈ 1040 CE) to the Gleissberg (1890 CE) Minima.
iii) Improving the time assignment to $\pm$ one year and better. Relative uncertainties of one year between two cores reduce the ability to identify the impulsive ^{10}Be episodes and thereby reduce the ability to detect SEP events in the past.
iv) An improved annual record of cosmic radiation is also of relevance for other applications such as the attempt to reconstruct total and spectral solar irradiance in order to quantify its role in climate change (Beer, 2013).

10. Discussions and Conclusions

i) We have identified and removed an offset in the cosmogenic data from the Dye-3 ice core (Beer *et al.*, 1990), and we have then combined that with data from North GRIP (Berggren *et al.*, 2009) to yield a record of the cosmic-ray intensity 1391 – 2013 with annual resolution. We refer to this as the paleo-cosmic ray (PCR) record.
ii) We have used the PCR data to estimate the near-Earth intensity of the HMF for the interval 1391 – 1983. We designate this estimate B(PCR-1).We have also used the PCR data to estimate the counting rate that would have been observed by a neutron monitor prior to 1951. We call this the pseudo-neutron-monitor (PNM) data.
iii) We have established that the large solar cosmic-ray events of 1942, 1949, and 1956 resulted in identifiable impulsive annual enhancements in the ^{10}Be record resulting in significant underestimates in B(PCR-1).
iv) We have identified a total of ten impulsive ^{10}Be episodes (13 years of enhanced ^{10}Be) with amplitudes similar to that of 23 February 1956 in the interval 1800 – 1983. The frequent correlation with great geomagnetic storms prior to 1942 leads us to propose that all of these impulsive enhancements were associated with solar cosmic-ray events in the past. Based on this, we estimate that the occurrence rate of such events is about seven per century. We note the absence of any larger events, suggesting that there is a limiting size to SEP events.

v) A second estimate, B(PCR-2), is obtained following the excision of the ten short lived solar cosmic-ray episodes identified in paragraphs iii) and iv).
vi) We have shown that large GLEs such as those of July 1946 and February 1956 may not be identified easily in annual cosmogenic data if they occur late in the second or in the third year of the solar cycle.
vii) The paleo-cosmic-ray (PCR) data, the PNM data, and the heliomagnetic magnetic-field (HMF) data are provided in the Electronic Supplementary Material.
viii) We conclude that the acquisition of ^{10}Be data with annual resolution from three more ice cores, commencing in 950 CE, would provide an improved ability to study the heliospheric processes throughout the sequence of Grand Minima between the Oort (1050 CE) and Gleissberg (1890 CE) Minima with a potentially broad field of applications.
ix) The theoretical model developed by Caballero-Lopez *et al.* (2004) presently restricts estimates of B(PCR) to ^{10}Be concentrations that imply B(PCR) greater than 2.5 nT.
x) A new Grand Minimum, which may occur within the next several decades, may provide new insights into many solar phenomena and potentially improve the inversion processes yielding more accurate B(PCR-2) and pseudo-neutron-monitor data during the Grand Minima throughout the past 10,000 years.

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Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

Appendix 1: The Annual ^{10}Be Data; Processing; Normalization; Removal of Climatic and Geomagnetic Effects

Two extended annual data sets of ^{10}Be concentrations are available at present; they are from Dye 3 in Greenland (65.18°N, 43.83°W, 2480 m a.s.l., Beer *et al.*, 1990) and NGRIP (75.10°N, 42.32°W, 2917 m a.s.l., Berggren *et al.*, 2009). The ^{10}Be data suffer from several uncertainties such as occasional loss of core; uncertain identification of year, and several long-term changes (*e.g.* climatic and geomagnetic changes that differ from place to place on the Earth). To minimize these uncertainties, the data from the two cores have been processed as follows. Throughout the following, $^{10}\mathrm{Be}(t)$ refers to the annual measurements of the ^{10}Be concentration:

- Time homogenization. We have used the time assignments for both records as determined by Berggren *et al.* (2009). The average $^{10}\mathrm{Be}(t)_{\mathrm{av}}$ was computed for each year; where there was a gap in one record the average was estimated using the other record.
- *Baseline correction*. As discussed in the Introduction, normalization of the cosmogenic data to the present epoch depended on the data from three ice cores; Dye 3 (Beer *et al.*, 1990), North GRIP (Berggren *et al.*, 2009), and South Pole (Bard *et al.*, 1997), and close examination showed that the Dye 3 decrease in ^{10}Be concentration between 1950 and 1960 was substantially greater than those for North GRIP and South Pole. The contemporary atmospheric transport and mixing of the ^{10}Be prior to sequestration in the polar

caps indicates that all three should be equal (Heikkila, Beer, and Feichter, 2009). We have used this equality to conclude that the concentrations observed at Dye 3 after 1950 were erroneously low. Applying a baseline correction based on the North GRIP and South Pole data to the Dye 3 concentrations, we have computed $^{10}\mathrm{Be}(t)_{\mathrm{stein}}$, the revised average for the normalization interval 1944 – 1987 (as used by Steinhilber *et al.*, 2012). The ratio $X_{\mathrm{stein}}(t) = {}^{10}\mathrm{Be}(t)_{\mathrm{av}}/{}^{10}\mathrm{Be}(t)_{\mathrm{stein}}$ was then computed for each year.

- *Removal of long-term variations of atmospheric origin*. The measured ^{10}Be and ^{14}C data contain significant contributions of climatic, atmospheric, and (in the case of ^{14}C) oceanic origin. Using the data from seven ice cores, and the most recent ^{14}C data, Steinhilber *et al.* (2012) isolated the cosmic-ray signal from these contributions of terrestrial and instrumental origin. The sampling times for the ^{10}Be and ^{14}C data ranged from one to ten years. To minimize aliasing from the Schwabe (11-year) and Hale (22-year) cycles, Steinhilber *et al.* (2012) converted the data to contiguous 22-year samples. After applying the baseline correction outlined above, we believe that this is presently the most reliable record of the long-term changes in the paleo-cosmic-ray intensity for the past 9400 years. We have therefore adjusted the annual data record [$X_{\mathrm{stein}}(t)$] to a new normalized annual record [$Y_{\mathrm{stein}}(t)$] where the 22-year averages of $Y_{\mathrm{stein}}(t)$ are consistent with the same time intervals in the baseline-corrected Steinhilber *et al.* (2012) data set. We stress that this removes the long-term contributions of atmospheric origin, while having minimal effect on the short-term production variations of $<$ 22-year duration.
- *Geomagnetic cut-off correction*. The geomagnetic dipole moment and the location of the geomagnetic poles have both changed significantly since 1391. For example, the geomagnetic dipole moment changed from 8.5×10^{22} to 8.0×10^{22} [Am^2], thereby reducing the geomagnetic cut-off rigidities; and as a consequence there was a ≈ 3 % increase in ^{10}Be concentration due to this effect alone between 1391 and 2013. The ratio $Y_{\mathrm{stein}}(t)$ was corrected to the 2013 epoch as detailed by McCracken (2004), and this is denoted $Y_{\mathrm{stein,GM}}(t)$.
- *Other* ^{10}Be *reference values*. As stated above, the annual ^{10}Be concentrations were initially expressed relative to the average for the interval 1944 – 1987 for consistency with Steinhilber *et al.* (2012). Two other reference values are convenient for computation and conceptual purposes, and they are also given in the Electronic Supplementary Material in the interest of uniformity among future workers. These reference values are: i) McCracken *et al.* (2004) introduced the nomenclature ^{10}Be(LIS) to represent the estimated value of the ^{10}Be concentration if the cosmic-ray local interstellar spectrum (LIS) were incident on Earth (that is, the modulation function $\Phi = 0$ MeV). The reader is referred to that article for discussion of the concept and its estimation. The annual values of $Y_{\mathrm{LIS,GM}}(t) = {}^{10}\mathrm{Be}(t)_{\mathrm{av}}/{}^{10}\mathrm{Be(LIS)} = 0.434 Y_{\mathrm{stein,GM}}(t)$. ii) Oh *et al.* (2013) combined the data from eight high-latitude NMs for the interval 1964 – 2010; NM data are frequently expressed as a percentage relative to the monthly value for February 1987. For consistency with this practice the pseudo-NM data (see next paragraph) in Figure 1 and in the Electronic Supplementary Material are expressed relative to that reference.
- *Data averaging used herein*. To this point, all of the calculations were made on an annual basis. In view of the large standard deviation of the annual data, two numerical filters were used in the figures and the discussions. They are:
  - A "(1,4,6,4,1) binomial filter" where the filtered (average) value of the data file $X(t)$ for year t is given by

$$X_{14,641}(t) = \{X(t-2) + 4 \times X(t-1) + 6 \times X(t) + 4 \times X(t+1) + X(t+2)\}/16. \quad (1)$$

  - The 11-year running average.

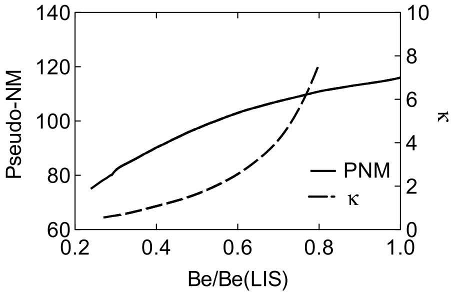

Figure 6 The look-up tables for the PNM data, and the diffusion coefficient [κ] used in the estimation of B(PCR).

Appendix 2: Estimation of the Pseudo-Neutron Monitor (PNM) Counting Rate

The neutron monitor provides one of the most important instrumental records of the intensity of the cosmic radiation near Earth. The record commenced in 1951, and since 1957 there have always been > 50 instruments in the world-wide network. They have provided a great deal of our understanding of the temporal, energy, and directional dependence of the > 1 GeV nucleon^{-1} cosmic radiation near Earth. The ^{10}Be data can be regarded as the output of a natural neutron monitor (Beer *et al.*, 2011) and it is convenient to use them to estimate the NM counting rate that would have been observed in the past. Using the procedure described by McCracken and Beer (2007), $Y_{\mathrm{LIS,GM}}(t)$ defined above was used to compute the annual PNM(t) using the look-up table in Figure 6.The resulting estimates are given in Figure 1 and Supplementary Table S-1. The relationship between the ^{10}Be data and the NM counting rates is substantially non-linear (Figure 5, McCracken and Beer, 2007). This is the consequence of two factors: i) the ^{10}Be response extending to lower energies, and ii) the amplitude of the modulation increasing rapidly towards lower energies. For example, the ratio between the percentage changes in the ^{10}Be and the NM data is 1.45 for the intensities observed during the sunspot minima of 1954 – 1996, while it increases to 4.4 during the Grand Minima such as the Maunder Minimum (1645 – 1715). This results in the differences that are evident for the highest cosmic-ray intensities in the top two panels of Figure 1.

Appendix 3: Estimation of the Heliospheric Magnetic Field, B(PCR)

This procedure is based on Caballero-Lopez *et al.* (2004) and McCracken (2007a). Using a 3D model of the heliosphere that included a solar-cycle-dependent current sheet, latitude-dependent solar-wind velocities, and the Hale cycle of solar magnetic fields, Caballero-Lopez *et al.* (2004) computed the production rate of ^{10}Be in the Earth's atmosphere as a function of the diffusion constant of cosmic rays [$\kappa(t)$] in the heliospheric magnetic field. In view of the high value of the standard deviation of the ^{10}Be data, we have averaged over the $\kappa(t)$ computed for the two polarities of the solar polar field, the resulting functional dependence being displayed in Figure 6. As a consequence, the Hale-cycle modulation of the ^{10}Be (due to particle drift effects; see Potgieter, 2013) remains in the tabulated data.

Caballero-Lopez *et al.* (2004) further developed the relationship between the diffusion coefficients [$\kappa(t)$] and the near-Earth HMF intensity [$B(t)$]. Writing B_{cal} and κ_{cal} for those parameters for the calibration interval, and $B(t)$ and $\kappa(t)$ for time t, we have

$$\kappa(t)/\kappa(t_{\mathrm{cal}}) = \left\{B(t_{\mathrm{cal}})/B(t)\right\}^{\alpha}, \quad (2)$$

where the exponent α takes into account the scattering properties of the heliospheric magnetic field. McCracken (2007a) used the annual neutron-monitor data and the satellite measurements of the near-Earth heliospheric magnetic field for the interval 1970 – 2005 to determine $\alpha = 1.75$. Figure 6 and Equation (2), together, provide the means to use the PCR to estimate the HMF in the past. This was done using a look-up table derived from the κ *versus* ^{10}Be curve in Figure 6. The Caballero-Lopez *et al.* method applies to values of $^{10}\mathrm{Be}(t)_{\mathrm{av}}/^{10}\mathrm{Be(LIS)} < 0.8$. Equation (2) of McCracken (2007a) shows that this corresponds to $B(\mathrm{PCR}) > 2.5$ nT, and consequently no estimates for $B(\mathrm{PCR}) < 2.5$ nT are given for those years in the Electronic Supplementary Material. This occurred for four years in the Spörer Minimum (1420, 1421, 1442.1, and 1460.1); six years in the Maunder Minimum between 1692.7 and 1698.7), and two years in the Dalton Minimum (1810 and 1811).

Appendix 4: Supporting Information

Table S1: Definition of columns in the data file given in the Electronic Supplementary Material.

Column 1. Date the recording was made. Prior to 1770, the date is that determined by Berggren *et al.* (2009). Subsequent to that date, the data were converted to calendar years using a cubic-spline interpolation. See Section 2 for further details.

Column 2. The year in which the majority of the ^{10}Be was produced in the stratosphere.

Column 3. $Y_{\mathrm{stein,GM}}(t)$ as defined in Section 2 for 1391 – 1950. This is the ratio between the average of the Dye 3 and North GRIP ^{10}Be concentrations for that calendar year, and the average for the interval 1944 – 1987 as used by Steinhilber *et al.* (2012) after correction for the baseline shift and other factors described in Section 2. Correction has been made for the changing strength of the geomagnetic dipole; the tabulated values correspond to the present-day strength of the geomagnetic dipole. The data in this column are given in the upper panel of Figure 1.

Column 4. $Y_{\mathrm{LIS,GM}}(t)$ as defined in Section 2 for 1391 – 1950. This is the estimated ratio between the average of the Dye 3 and North GRIP ^{10}Be concentrations for that calendar year, and the value that would be observed if the local interstellar spectrum (LIS) of the galactic cosmic radiation were incident on Earth, the value corresponds to the present-day strength of the geomagnetic dipole.

Column 5. 1391 – 1950; Annual estimates [nT] of B(PCR-1) as described in Section 3 and plotted in the upper panel of Figure 2. This is the estimated strength of the heliospheric magnetic field near Earth, before the removal of the ^{10}Be produced by solar energetic particle events. See Appendix 3 regarding the present-day restriction of estimates to B (PCR) > 2.5 nT. These upper limits are given in the tabulation as < 2.5 nT.

Column 6. Annual average estimates of the pseudo-neutron-monitor counting rate. For 1951 – 2013; annual average instrumental neutron-monitor-counting rate. For 1391 – 1950; annual estimate based on the ^{10}Be record. All data are normalized to the value for February 1987. These data are given in the middle panel of Figure 1.

Column 7. Annual average of selected high-latitude neutron monitors. 1965 – 2010 from Oh *et al.* (2013). 1951 – 1964, Climax, normalized to Oh *et al.* (2013), after correction for altitude and cut-off rigidity; 2011 – 2014, Oulu normalized to Oh *et al.* (2013).

Column 8. 1775 – 1950; Annual estimates [nT] of B(PCR-2) as described in Section 5 and plotted in the lower panel of Figure 2. This is the estimated strength of the heliospheric magnetic field near Earth, after the removal of the ^{10}Be produced by solar energetic-particle events.

Column 9. The ^{10}Be impulsive enhancements identified by the selection criterion described in Section 4, and verified by subtraction of the 11-year and longer variability (see Figures 3 and 4). These data are given as the percentage increase in ^{10}Be concentration compared to the concurrent mean. Note that these data are tabulated against the year in which they occurred in the ^{10}Be time series; no allowance has been made for the one-to-two year delay between production and sequestration in polar ice (see Section 4).

Table S2: A summary of some acronyms used in the article. Further descriptions are given in the text. The references are to the initial definitions of these acronyms.

PCR Paleo-Cosmic ray Referring to estimates of the cosmic-ray intensity based on measurements of the cosmogenic radionuclides preserved in polar ice (McCracken and Beer, 2007).

PNM Pseudo-neutron monitor Referring to estimates of the neutron-monitor counting rate that would have been observed prior to the commencement of the NM record in 1951. In this article, based on measurements of the cosmogenic radionuclides preserved in polar ice (McCracken and Beer, 2007).

B(PCR-1) Estimate of the field strength of the heliomagnetic field derived from the PCR data before removal of the contributions made by cosmic rays produced by the Sun (Section 3 of this article).

B(PCR-2) Estimate of the field strength of the heliomagnetic field derived from the PCR data after removal of the contributions made by cosmic rays produced by the Sun (Section 3 of this article).

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