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400 years of large fluence solar proton events

K. G. McCracken[1], D. F. Smart[1], M. A. Shea[1], and G. A. M. Dreschhoff[1]

[1]Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742
[2]Air Force Research Laboratories, Space Vehicles Directorate, Hanscom Air Force base, Bedford, Mass 01731
[3]Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045

Abstract. The geophysical significance of the thin nitrate-rich layers found in both Arctic and Antarctic ice cores is examined in detail. The nitrate layers have a short time scale (<6 weeks) and are highly correlated with major solar-terrestrial disturbances. A one to one correlation is established between the seven largest solar proton events (SPE) observed since 1942, and nitrate layers that correspond to the same date. A conversion factor is established between nitrate concentration and SPE fluence, and this shows that there were 125 SPE in the period 1561-1950 with a >30MeV fluence $>1.0\text{x}10^9$ /cm^2 . A cumulative probability distribution derived from these data is in good agreement with a distribution derived from satellite observations, leading to the conclusion that the nitrate layers will allow analysis of the occurrence of SPEs into the past. The high fluences observed, and the existence of episodes of 0.5-1 major SPE per year is shown to have resulted in the production of significant quantities of cosmogenic ^{10}Be.

1 Introduction

Over the past 15 years there have been a number of publications that have advanced the hypothesis that short term (approximately two month or less) increases in the nitrate component of polar ice are the consequence of solar proton events (SPEs). (e.g., Dreschhoff and Zeller, 1990; Zeller and Dreschhoff, 1995). The associations have been a long way removed from one to one, and as a consequence the hypothesis has been regarded as plausible but unproven.

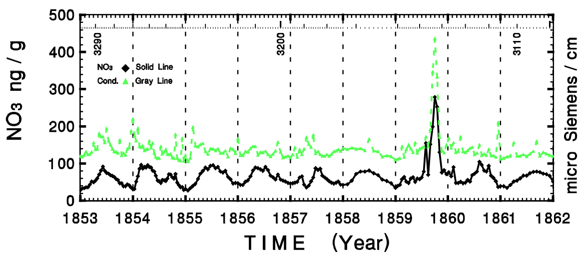

Fig.1. The impulsive nitrate event associated with the Carrington white light flare of 1 September, 1859. The scale along the top of this and other figures gives the sample number in the data deposited with World Data Center A for Glaciology.

A comprehensive study has now been made of 156 such impulsive nitrate events in order to establish their nature, and to then use them to investigate the occurrence of large SPE over the period 1561-1950. Portion of this work is described elsewhere in this conference (McCracken et al, 2001a) and will be published in detail later (McCracken et al, 2001b, 2001c).

2 Analytical Procedure

The data reported here comes primarily from a 125.6m ice core from Summit, Greenland (72ºN, altitude 3210m), with other data from two short cores from Windless Bight, (78ºS), Antarctica. Figures 1, 2 and 3 present the

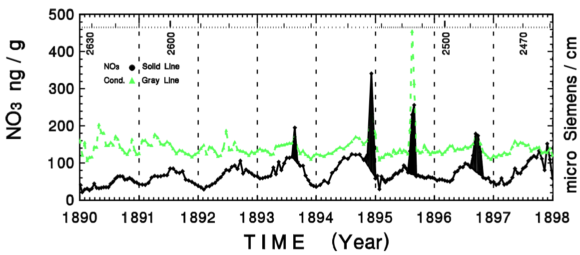

Fig. 2 The nitrate data for the interval 1890-1898. Four of the five events are blacked in to illustrate the procedure used to estimate $\Sigma C(n)$.

nitrate records for portions of those cores. The ice cores are sampled to yield about 20 contiguous samples per year. NO_3 concentrations (in nanograms of nitrate/gram of water) and electrical conductivities (in micro-Siemens/cm) are measured for each sample. Figures 1 and 2 display data from the Greenland ice core and an annual variation is clearly evident due to transport of NO_3 from lower latitudes. This annual behavior is well defined for ~90% of the Greenland core and is used to interpolate time between 33 well known reference horizons due to volcanic eruptions. We estimate that our assigned times are accurate to within ±2 months for 90% of the Greenland core, and ±1 year where the annual wave is poorly defined.

Examination of the nitrate record shows that there are many impulsive anomalies, often of amplitude greatly in excess of the annual variation, and of duration of two months

Correspondence to: mccracke@ipst.umd.edu

or less. For example, in Fig 1 the persistent annual variation in the nitrate signal is interrupted by two impulsive events, the second being the largest such impulsive event in the whole Greenland nitrate record, 1561 - 1991. The time of occurrence of this second nitrate event is estimated with confidence to be 1859.75 ±0.2. Carrington (1860) observed a white light flare on 1 September 1859, and it was followed by an exceptionally large geomagnetic storm, which had the very rapid sun - earth transit time of 17.1 hours (Cliver et al., 1990). Thus the largest impulsive NO_3 event in the interval 1561-1991 is closely associated in time with a period of exceptional interplanetary and geomagnetic disturbance. The probability of this association, by chance, is 7.8×10^{-4}.

Figure 2 presents one of several episodes of very frequent nitrate events in our data. The episode in Fig.2 was coincident with a period of exceptionally large and frequent geomagnetic storms. A similar episode occurred during the period 1600-1620, at which time auroral and sunspot numbers indicate that the sun was very active. These correlations further strengthen the association of the nitrate events with periods of exceptional solar activity.

To quantify each of the impulsive events, the excess nitrate, over and above the annual variation, was calculated. We estimated the annual variation at the time of the impulsive event by visual inspection, and the integral of the event above that annual wave was then calculated. Figure 2 illustrates this procedure. Representing the nitrate concentration in the nth sample by C_n, then for a sample length of L cm, and ice/firn density of ρ, the NO_3 deposited on the polar surface by a single impulsive event summed over the several time samples in the event is $\Gamma = \rho L \ \Sigma C(n)$ nanogram / cm^2. We use Γ to quantify the nitrate events and will later use it to estimate the fluence of the SPE that was associated with the nitrate event.

3 Comparison with the cosmic ray record.

Figure 3 presents the nitrate data from Antarctica during the interval 1945-1948. The Carnegie Type C ionization chamber network recorded a very large solar cosmic ray event on 25 July, 1946 (Forbush, 1946), coinciding with the nitrate event in Fig 3 within the ±2 month timing accuracy of our data. We have examined the nitrate data at the times of the five solar events recorded by the ionization chambers or muon telescopes (1942,1946,1949,1956 and 1960) and two large "satellite era" events (1972, 1989) and there are nitrate events for all seven events. They all exhibit the same degree of association in time observed for the 1946 event in Fig.3. The statistical probability that the seven impulsive nitrate events, and the seven SPE, would exhibit this close degree of correlation by chance is $<1.0 \times 10^{-6}$. In further support of the identification of the nitrate events with SPE, Vitt et al (2000) have shown that the 1972 and 1989 SPE would have generated 10-20% increases in the "odd nitrogen" (the progenitor of the nitrate precipitated to earth)

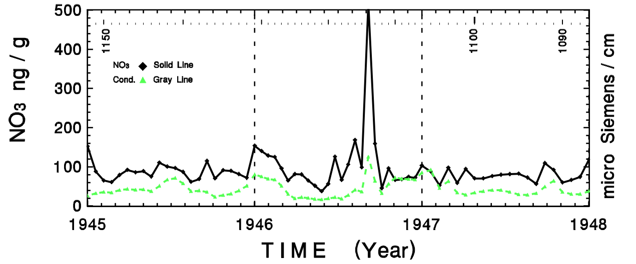

Fig. 3 The nitrate data from Antarctica at the time of the ground level cosmic ray event of 25 July, 1946.

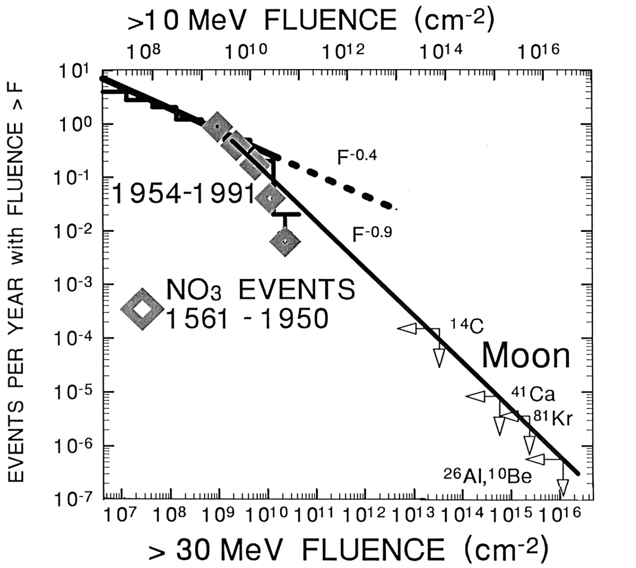

Fig.4. Cumulative probabilities of the SPEs observed by satellite, and derived from the nitrate data. The diamond shaped symbols refer to the nitrate data; the histogram and lines to the satellite data and fluence limits derived from cosmogenic isotopes in moon rocks.

in the polar stratosphere. On the basis of all of the above evidence, we conclude that the impulsive nitrate events such as in Fig.1-3 are the direct consequence of the ionization of the polar stratosphere by solar cosmic rays.

Using previous estimates and measurements of the fluence of the four most recent of the above events, 1956-1989 (Shea and Smart, 1990), and Γ as defined above, the conversion factor from nitrate to fluence was determined. Using this calibration, fluences were estimated for the 125 nitrate events that represent SPE with an omni-directional fluence (>30MeV) of $>1.0 \times 10^9$ /cm^2. From these, we have derived the cumulative probabilities for the occurrence of SPE displayed in Fig.4. As outlined elsewhere (McCracken et al, 2001c), we estimate that seasonal factors mean that the Greenland ice core only sees 75% of the SPE, and consequently, the probabilities in Fig.4 have been normalized to 100% "efficiency" by multiplication by 1.33. Fig 4 also presents the cumulative probabilities based upon satellite data given by Reedy (1996). Note the good agreement between the NO_3 data, and the direct spacecraft measurements. This provides further confirmation that the impulsive nitrate events provide a quantitative measurement of SPE fluence throughout the period 1561-1993.

The slope of the probability distribution in Fig. 4 becomes much steeper for >30 MeV fluences larger than 6×10^9/cm^2. Our two highest fluence bins exhibit this rapidly decreasing probability, and since they contain a total of eight SPE, this rapid decrease in probability is statistically significant. Elsewhere (McCracken et al.,2001c) we propose that this feature is due to the effects of the ion-wave interactions that give rise to the streaming limited fluxes observed by satellite instruments in large solar proton events (Reames, 1999).

4 The production of cosmogenic isotopes by SPE.

The fluences of the events in Fig. 1 and 2 are large compared to the majority of the SPE observed over the past 50 years. Thus they are estimated at 18.8×10^9/cm^2 for the "Carrington" event of 1859 in Fig. 1; and at 2.3, 7.7, 11.1, 8.0 and 3.1×10^9/cm^2 respectively for the five in Fig.2. In addition, Fig. 2 illustrates that there are episodes in which large SPEs occur at the very high rate of 0.5 to 1 per year. These high fluences, and high frequencies mean that SPEs may have had a greater impact on some interplanetary and terrestrial phenomena than has been appreciated previously.

Lal and Peters (1962) made early estimates of the cosmogenic yields from SPEs and concluded that the large SPEs observed prior to 1961 may have generated measurable quantities of ^{14}C and ^{10}Be. More recently, Masarik and Beer (1999) have used a detailed mathematical model to that show that neutrons contribute 99% of the cosmogenic nuclides produced in the atmosphere. On that basis, we have used the neutron data obtained during the large "ground-level event" (GLE) cosmic ray increase that occurred on 23 February 1956 (Meyer et al., 1956), and other data from the GLEs of 1959 and 1960 to estimate the production of ^{10}Be during the GLE of February, 1956. Allowing for the rapid increase in neutron intensity with altitude during a GLE; for the residence time of the ^{10}Be in the atmosphere; and for precipitation effects; we estimate that the ^{10}Be production rate for the event of 23 February, 1956 was 3.1×10^2 atoms /g for a SPE fluence of 10^9 cm^{-2}.

Beer et al. (1990) reported annual values for the concentration of ^{10}Be for the period 1783-1985 in which individual 11-year (Schwabe) cycles are clearly evident with amplitudes of 20-30%. The standard deviation of the Beer et al. data is given as 4-10% on annual data; for this reason a 3% increase as computed above for the 1956 GLE would not be statistically significant. However, the fluences quoted above indicate that the five large events in the interval 1893-1897 (Fig. 2) had a total >30 MeV fluence of 32.1×10^9 cm^{-2}, compared to 1.0×10^9 cm^{-2} for the 23 February 1956 event (Shea and Smart, 1990). Thus, if the SPEs in 1893-1897 had similar rigidity spectra to the 1956 event, they would have produced a total of 0.99×10^4 atoms/g of ^{10}Be in the Beer et al. (1990) ice core, and this would be discernible in the data.

To examine this prediction, Fig. 5a displays the Beer et al (1990) data for the interval 1870-1944. Figure 5b displays our estimate of the year to year variation of the solar cosmic ray produced ^{10}Be. These estimates have used all of the SPE identified in the nitrate data for this period with a fluence $>1.0 \times 10^9$ cm^{-2} (see McCracken et al., 2001b); and have used the cumulative distribution from Fig.4 to include SPE with fluences $>1.0 \times 10^8$ cm^{-2}, to yield the annual value of SPE fluence. The ^{10}Be production rate was taken as 3.1×10^2 atoms /g for a fluence of 10^9 cm^{-2} as estimated above. A three point time series filter (sample weights of 1,2,1) has been applied to all of the annual data in Fig. 5. Examination of Fig. 5b shows a prolonged enhancement in predicted ^{10}Be

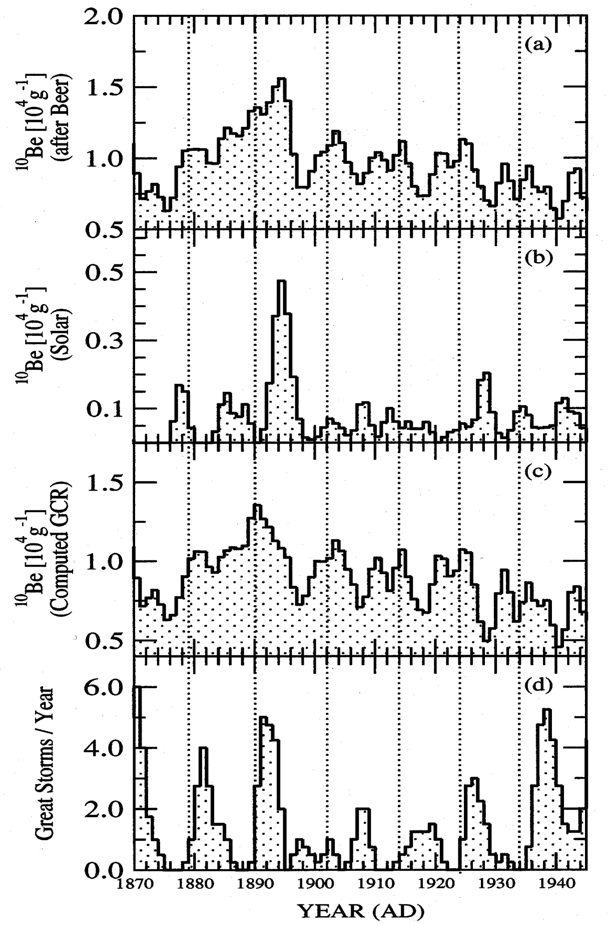

Fig.5 Illustrating the effect of an intense episode of SPE upon cosmogenic ^{10}Be. (a) C_{obs}, the observed ^{10}Be. (b) C_{spe}, the ^{10}Be estimated to have been produced by solar cosmic radiation. (c) $C_{gcr} = C_{obs} - C_{spe}$, (d) Very large geomagnetic storms.

between 1892-1896, reaching an amplitude of 0.39×10^4 atoms/g. This amplitude is comparable to that of the 11-year modulation of the galactic cosmic radiation, and approximately out of phase with it, so a solar component of this magnitude would make a substantial change to the character of the 11-year variation in the ^{10}Be data.

Writing the observed ^{10}Be concentration as C_{obs} , and the solar and galactic cosmic ray (GCR) produced ^{10}Be concentrations as C_{spe} and C_{gcr} respectively, then $C_{gcr} = C_{obs} - C_{spe}$. Figure 5c displays the time variation of C_{gcr} computed in this manner and in the following discussion we compare the observed concentration C_{obs}, and the computed quantity

C_{gcr} for the period 1889-1901 (the 13th sunspot cycle). To aid discussion, Fig. 5d displays the occurrence of very large geomagnetic storms.

The 11-year variation in the GCR has been observed instrumentally since 1936. Invariably, it attains its highest value during sunspot minimum; it commences to decrease about one year thereafter; and is close to its minimum value about 1-2 years after the maximum in the smoothed sunspot number is achieved. The decrease is often in the form of downward steps associated with major geomagnetic storms. Now consider the observed concentration of ^{10}Be in Fig. 5a. The concentration continued to rise (by >20%) for the period 1890-1894; that is for 5 years after sunspot minimum and after the onset of major geomagnetic activity. It did not reach its maximum value until one year after sunspot maximum in 1893. As outlined above, this behavior is totally inconsistent with any of the direct measurements of the 11- year variation since 1936.

Consider, however, the computed GCR intensity ($C_{gcr} = C_{obs} - C_{spe}$) in Fig. 5c. It was decreasing in 1892 within a year of the onset of major geomagnetic activity, and it declined steadily thereafter to a minimum about 1896-7. The behavior in Fig. 5c is similar in character to that of the 11-year variations observed since 1936, and during the other sunspot cycles in Fig. 5a. We conclude that the anomalous 11-year variation evident in the interval 1890-1895 in Figure 5a is not explicable in terms of the 11-year modulation of the GCR, alone. However, it is consistent with there being a solar cosmic ray component as computed using the fluences tabulated in McCracken et al. (2001b). Comparison of Fig. 5a and 5b shows that this solar component sometimes may be sufficiently large to greatly alter the amplitude and phase of the time variations of ^{10}Be.

5 Conclusions.

This paper has demonstrated that the impulsive nitrate events observed in suitable ice core are the direct result of the ionization of the polar atmosphere by solar cosmic rays. A conversion factor between nitrate and fluence has been established, which yields a good agreement between the cumulative probability curves for SPE derived from the nitrate, and satellite data. It is therefore concluded that these nitrate events will allow quantitative analysis of SPE for several millennia into the past. The high fluences observed, and the existence of episodes with as many as 0.5-1 large SPE per year, are shown to have produced appreciable and observable quantities of cosmogenic ^{10}Be.

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