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Solar cosmic ray events for the period 1561–1994
2. The Gleissberg periodicity

K. G. McCracken
Institute for Physical Science and Technology, University of Maryland, College Park, Maryland, USA

G. A. M. Dreschhoff
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas, USA

D. F. Smart and M. A. Shea
Air Force Research Laboratory, Space Vehicles Directorate, Hanscom Air Force Base, Bedford
Massachusetts, USA

Abstract. A total of 125 large fluence solar proton events identified from the nitrate deposition in ice core from Greenland for the period 1561–1950 are examined in an exploratory study of the geophysical information that will be available from such data in the future. These data have been augmented with ionospheric and satellite data for the period 1950–1994. There were five periods in the vicinity of 1610, 1710, 1790, 1870, and 1950, when large >30 MeV proton events with fluence greater than 2×10^9 cm^{-2} were up to 8 times more frequent than in the era of satellite observation. There is a well-defined Gleissberg (approximately 80 year) periodicity in the large fluence proton events, with six well-defined minima, two in close association with the Maunder and Dalton minima in sunspot number. The present "satellite" era is recognized as a recurrence of this series of minima. Comparison of the total solar proton production for the five Gleissberg cycles since 1580 shows that the cycle 1820–1910 was the most active followed by the cycle 1580–1660. The present Gleissberg cycle is one of the least effective in the production of solar proton events at Earth. It is shown that the solar and solar proton event data both indicate that the Maunder Minimum ended about 1700, 16 years before the commonly accepted date of 1716. It is proposed that the delayed "switch on" of aurorae after the Maunder Minimum is due to the changing nature of the solar corona from "Maunder Minimum" conditions to the more active conditions of the Gleissberg cycle, and a physical mechanism is proposed in which variations in the coronal densities modulate the efficiency of solar proton event production throughout the Gleissberg cycle. The "streaming limited fluence" for >30 MeV protons is estimated to be $6-8 \times 10^9$ cm^{-2}, and the rapid decrease in the probability of occurrence of solar proton events observed in the vicinity of this fluence is proposed to be due to this effect.

1. Introduction

In a companion paper, *McCracken et al.* [this issue] show that the impulsive nitrate events observed in polar ice cores [*Dreschhoff and Zeller*, 1990; *Zeller and Dreschhoff*, 1995] are the consequence of the occurrence of large fluence solar proton events (SPEs) at Earth. Using this technique, solar proton events can be usually dated to within ±2 months for the period 1561–1950, and *McCracken et al.* [this issue] have detailed the computations that allow an estimate of the >30 MeV fluences for the 125 impulsive nitrate events with fluences $>1.0 \times 10^9$ cm^{-2} in that interval. In this second paper these impulsive nitrate events together with satellite and other data for the period 1950–1994 are used to study the manner in which SPEs have varied with time over the period 1561–1994.

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2. Occurrence of Large Solar Proton Events in the Interval 1561–1994

As described in sections 4 and 5 of *McCracken et al.* [this issue], there were 156 impulsive nitrate events (>27 ng g^{-1}) identified in the Greenland ice core between 1561 and 1950. (The quantity ng g^{-1} is used to quantify the nitrate deposition. This is a measure of the total nitrate concentration that would have been observed if all the nitrate in that event had been precipitated into a single sample.) Figure 1 displays the occurrence of solar proton events between 1561 and 1994. These events all have a >30 MeV omnidirectional fluence above 1.0×10^9 cm^{-2}. Events from 1561 to 1950 have been derived from the Greenland ice core data; events after 1950 are from ground level and satellite data [*Shea and Smart*, 1990, 1994]. After allowance for the density of the ice core, 31 of the 156 nitrate events identified by *McCracken et al.* [this issue] fell below the >30 MeV fluence cutoff of 1.0×10^9 cm^{-2}, leaving the 125 events that are used throughout this companion paper.

To further quantify the occurrence of solar proton events, Table 1 lists the observed Schwabe (11 year) cycles against the

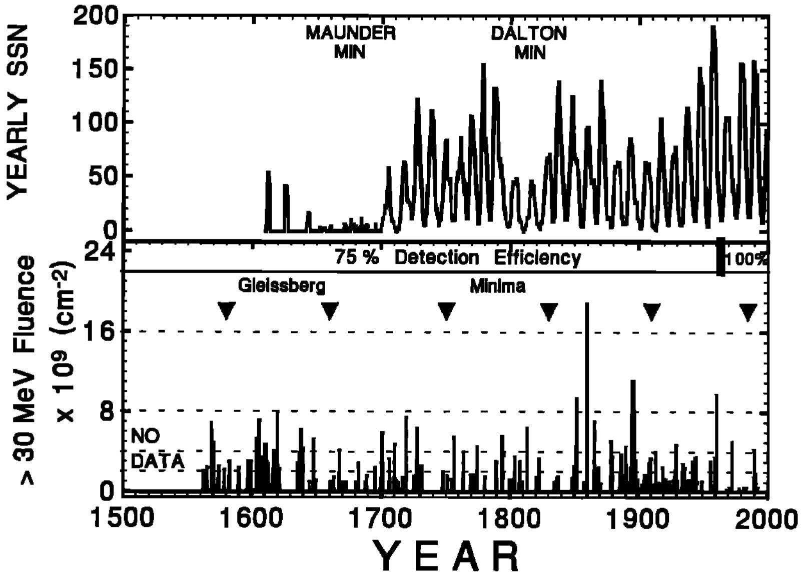

Figure 1. The times of occurrence of >30 MeV solar proton events with fluence exceeding 1.0×10^9 cm^{-2} as derived from the nitrate data (1561–1950) and from ionospheric and satellite data since 1950. The times assigned to the minima of the Gleissberg cycle are shown by the triangular markers. The annual international sunspot numbers are given in the top panel.

number of SPEs identified from the nitrate data for the 35 Schwabe cycles from 1567–1954. (This paper uses several terms to identify various solar cycles as follows: Schwabe cycle, the ~11-year periodicity in sunspots [*Schwabe*, 1844; *Waldmeier*, 1961]; Hale cycle, two consecutive 11-year sunspot cycles constituting the period in which the magnetic polarity of bipolar sunspots complete a cycle of change [*Hale*, 1908; *Hale and Nicholson*, 1925]; Gleissberg cycle, originally, the maximum sunspot number amplitude modulation having a period between 80–100 years in length. The current usage is any solar-terrestrial phenomena having a modulation period of ~80–100 years [*Gleissberg*, 1958, 1965, 1966].) The minima of the solar cycles from 1611 to the present are from *McKinnon* [1987]; minima prior to 1611 have been assumed to be in 1567, 1578, 1589, and 1600. Two events from Table 1 of *McCracken et al.* [this issue] occurred prior to 1567 and are not included in Table 1.

It is important to recall that the data in Figure 1, Table 1, and elsewhere in this paper are from the Greenland ice core only. In addition, there is a variability in the conversion factor from nitrate to fluence which is poorly quantified at this time (see section 8 of *McCracken et al.* [this issue]). For example, the known precipitation processes indicate that the fluence of SPEs occurring in the northern summer may be underestimated or even missing. Thus the event of July 25, 1946, probably the largest fluence event in the "instrumental" cosmic ray era, is missing from Figure 1 even though the nitrate deposition from this event is large in the Antarctic ice core as illustrated in Figure 4b of *McCracken et al.* [this issue].

The detection efficiency bar in the middle of Figure 1 should be noted. Since about 1950, satellite and other ground-based detectors have provided 100% detection efficiency; however, prior to about 1950 the detection sensitivity is less. In addition, as discussed in the previous paragraph, we are using only the Greenland ice core for this analysis. We estimate the detection efficiency prior to 1950 to be ~75%, and thus the Greenland data underestimate SPE occurrence by a factor of about 1.33. Whenever we have made comparisons over the entire interval 1561–1994, the SPE frequencies derived from the Greenland data have been increased by this factor to normalize the data to the present era. None of the conclusions of this paper are critically dependent upon the value of this normalization factor within the range 1.0–2.0. The normalized frequency per Schwabe cycle is given in Table 1.

In addition to the seasonal variation in conversion factor, the experimental errors discussed in connection with Table 2 of *McCracken et al.* [this issue] mean that the average conversion factor may have an uncertainty up to ±50%. However, the uncertainties in the conversion factor from nitrate deposition to fluence will be identical for the whole period 1561–1950, and all conclusions regarding the time and fluence dependence of solar proton events for that period will be unaffected by these errors. While there may be a discontinuity in the accuracy of the fluence estimates in the vicinity of 1970, as detailed in section 1 of *McCracken et al.* [this issue], the conclusions in this paper have been tested and shown to be unaffected by the degree of error involved.

Figure 2 displays the two-cycle running average of the number of large fluence solar proton events and the two-cycle running average of the maximum value of the annual sunspot number for each Schwabe (11 year) sunspot cycle. The starting and end dates for each Schwabe sunspot cycle, as well as the estimates of the maximum sunspot numbers prior to 1700, are

Table 1. Distribution of the Large Solar Proton Events (>30 MeV Fluence $>2.0 \times 10^9$ cm^{-2}) Observed During Schwabe (11 Year) Solar Sunspot Cycles

	SPE per Cycle						
	0	1	2	3	4	5	6
Number of cycles	7	6	11	7	2	1	1
Normalized frequency	0	1.3	2.7	4	5.3	6.7	8

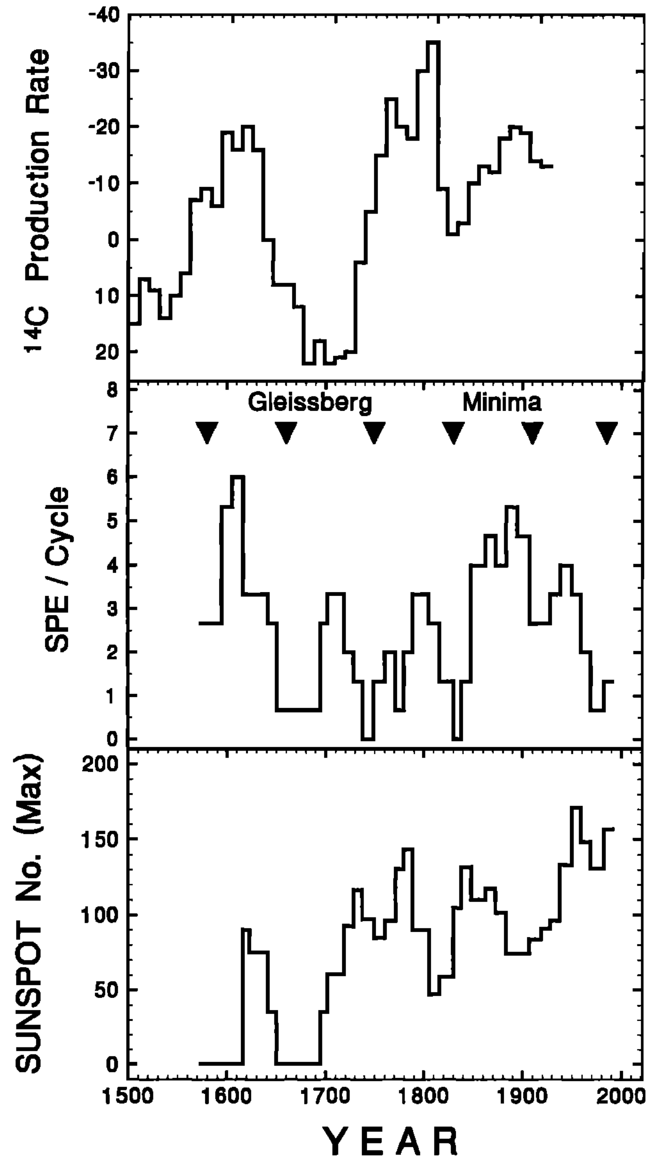

Figure 2. The frequency of occurrence of solar proton events and the maximum annual sunspot number for the period 1561–1994. The data are averaged by a two solar cycle running means. Prior to 1950 the detection efficiency (for data from the northern polar cap) is taken to be 75%, and the data displayed are normalized by multiplication by 1.33. The data after 1950 have equal sensitivity throughout the year, and no adjustment has been necessary. The times assigned to the minima of the Gleissberg cycle in Figure 1 are shown by the arrows. The ^{14}C production rates as computed by *Stuiver and Quay* [1980] are relative to the average for the period.

those given by *Eddy* [1976]. For this figure we have selected only those solar proton events having a >30 MeV fluence $>2 \times 10^9$ cm^{-2}. We have excluded events with fluence $<2 \times 10^9$ cm^{-2} since there is a small probability that a few of the events prior to the consolidation to ice (about 1900) may be of meteorological origin (section 3 of *McCracken et al.* [this issue]). Since the solar proton event data in Figure 2 is a key feature of the following discussion, the use of the higher cutoff fluence is desirable to remove any doubt concerning their reliability.

Figure 2 shows that the normalized frequency of these large fluence solar proton events has varied strongly with time since 1561 from zero for two separate Hale periods of 22 years (centered on 1744 and 1833) up to five and six per Hale cycle (centered on 1889 and 1611, respectively). Table 1 indicates that the individual Schwabe cycles may have higher normalized frequencies, ranging from 0 to 8. For example, after normalization, we estimate that there were eight large solar proton events for the Schwabe cycle that peaked about 1605 and seven large events for cycle 13 which peaked about 1893 [*McKinnon*, 1987]. For the period 1650–1699 in the Maunder Minimum the normalized frequency of events (>30 MeV fluence $>2.0 \times 10^9$ cm^{-2}) is 0.6 event per Schwabe cycle. Thus the event frequency for these large fluence SPEs averaged over periods of approximately two decades varies by a factor of 10 or more over the interval 1561–1994.

Referring again to Figure 2, we find that the normalized frequency of large SPEs in the "satellite measurement era" (Schwabe cycles 20–22, 1964–1996) averaged about one event per Schwabe cycle. This is to be compared with normalized frequencies of 6–8 SPEs per Schwabe cycle in the vicinity of 1605 and 1893 as noted above and in Table 1.

3. Gleissberg Periodicity in Solar Proton Event Frequency

It has long been recognized that the sunspot number exhibits a "long" period of 80–90 years that appears as an amplitude modulation of the Schwabe cycle [*Sonett et al.*, 1997], and this is commonly referred to as the Gleissberg cycle [see *Hoyt and Schatten*, 1997, chapters 9 and 10; *Gleissberg*, 1966]. The Gleissberg cycle is well defined in the sunspot number plot in Figure 1; however, the short duration of the data record (300 years, about three Gleissberg cycles) and uncertainty in the data prior to about 1800 limits the ability to study or characterize its properties with certainty. The Gleissberg cycle is also evident in terrestrial phenomena such as atmospheric temperature, precipitation, biota, and possibly the eustatic sea level [*Fairbridge*, 1967; *Hoyt and Schatten*, 1997], and it is recognized as an important feature of the Sun-Earth environment.

Figure 2 (and later Figure 4) shows that the frequency of occurrence of large solar proton events (>30 MeV fluence of 2×10^9 cm^{-2}) exhibits a very clear Gleissberg periodicity. There are five well-defined maxima in the vicinity of 1610, 1710, 1790, 1870, and 1950 with an average repetition period of about 85 years. The lower graph in Figure 1 also indicates that the Gleissberg periodicity is also evident for solar proton events having a fluence $>1 \times 10^9$ cm^{-2} above 30 MeV.

Referring to Figures 1 and 2, note the clearly defined minima of the Gleissberg periodicity in the solar proton event data (the small phase lags between the data are discussed in section 5). Two of the minima are closely associated in time with the well-known Maunder (1645–1700) and Dalton (1810–1830) Minima of the sunspot number. Four other minima near 1560–1580, 1750, 1910, and the vicinity of 1980 appear to be members of the same approximately 80- to 85-year sequence. Thus the satellite era of observations has coincided with a recurrence of this persistent series of minima in solar proton event frequency.

Satellite measurements have shown that there are ~80 significant solar proton events per Schwabe cycle [*Shea and Smart*, 1999], while less than eight large fluence events are seen in the nitrate record per cycle. (*Shea and Smart* [1999] used the criterion for significant events as any individual event with a

Table 2. Estimates of the Total Fluence of Protons >30 MeV for the Five Gleissberg Cycles, 1580–1985[a]

Gleissberg Cycle	Average SSN	Number of SPE	Fluence of Five Largest SPE	Estimated Fluence (Whole Cycle)	Ranking (by Fluence)
1580–1660	unknown	21	31.6×10^9	35.9×10^9	2
1660–1750	58.4	8	27.4×10^9	31.2×10^9	3
1750–1830	95.3	10	25.7×10^9	29.2×10^9	5
1830–1910	97.8	19	54.9×10^9	62.4×10^9	1
1910–1985?	128.4	10	26.7×10^9	30.3×10^9	4

[a] Abbreviations SSN, sunspot number; SPE, solar proton event.

>10 MeV flux equal to or greater than 10 protons cm^{-2} s^{-1} $ster^{-1}$.) We now investigate the use of the relatively few SPEs seen in the nitrate record to characterize the whole of the SPE cumulative normalized probabilities for each Schwabe cycle. Using the tabulations of *Shea and Smart* [1990, 1994] and *Smart and Shea* [1997], we form the ratio between the total fluence for all the significant solar proton events in a Schwabe cycle, and the sum of the fluences of the five largest solar proton events. (To determine the fluence for each of the five largest events in a Schwabe cycle, the fluence of major discrete injections within an ~14-day period were summed as one event. Thus the total fluence for the October 1989 sequence of activity includes the four major discrete proton events on October 19, 22, 24, and 27.) For Schwabe cycles 19, 20, and 22 the ratio is remarkably constant (1.16, 1.15, and 1.10, respectively), and this indicates that we may estimate the total solar proton event output, provided we know the fluences of the five largest events from the ice cores. The ratio for cycle 21 is 1.66; however, since the highest solar proton event fluence during this cycle was only 4.4×10^8 cm^{-2}, and the total fluence for the whole cycle was very low, we propose that this ratio is not indicative of the average solar proton fluence for the majority of Schwabe cycles within a Gleissberg cycle.

Using the average of the fluence ratios for Schwabe cycles 19, 20, and 22, Table 2 presents estimates of the total solar proton fluence for each of the five Gleissberg cycles evident in Figures 1 and 2. The averages of the peak annual sunspot indices for the constituent Schwabe cycles are given as well as the number of solar proton events with fluence $>2.0 \times 10^9$ cm^{-2} within the cycle.

Table 2 indicates that the total number of large fluence solar proton events and their total integrated fluence at Earth has not varied by more than a factor of 2–2.6 from one Gleissberg cycle to another. Table 2 further shows that our total experience of solar proton events, both with ground-based instruments and with satellites, has been for one of the least active Gleissberg cycles in the past 433 years. Furthermore, 80% of the events and fluence for the Gleissberg cycle starting in 1910 occurred prior to 1960. This is a further indication that the solar proton events that were observed during the satellite era were far from typical of the solar proton events that occurred during the previous four centuries.

Table 2 and Figure 1 show that the Gleissberg cycle 1830–1910 had the highest solar proton event fluence in the period under study. There are good magnetic and solar records for most of that period (see section 6), and retrospective analyses to determine whether there are features that could explain the high frequency of large solar proton events will be worthwhile.

Table 2 shows that the Gleissberg cycle 1580–1660 had the highest number of solar proton events and the second highest total integrated solar proton event fluence in the past 433 years. The sunspot data are so sketchy that it has been previously impossible to use them to make quantitative comparisons between the solar activity prior to 1700 and that of the well-instrumented 20th century. The solar proton data derived from the nitrate deposition in polar ice provide the first quantitative measurement of the solar activity in the vicinity of 1600, and we conclude that the Sun was as active then as in the 19th and 20th centuries.

Consider the immediate implications of Figure 2 and the previous discussion. We have found that the present "satellite epoch" is a period of abnormally low solar proton event frequency, and this period (1967–1994) is close to the sixth member of the series of minima of the Gleissberg periodicity in the interval 1561–1994. Our discussion has shown that the normalized solar proton event frequency has increased rapidly following the earlier minima to the vicinity of 6–8 large SPEs per Schwabe cycle. Repetition of that behavior would mean that the solar proton event frequency and the total fluence could increase by a factor of 6 to 8 possibly commencing in the next Schwabe cycle. Should this prediction be correct, the Earth will experience substantially more solar proton events and solar cosmic ray ground level events than has been our experience during the period since 1950. It may approximate the situation in the period 1940–1950, during which time four large ground level events were observed with the relatively insensitive ionization chambers in use at that time [*Smart and Shea*, 1991].

We note, however, another possibility with respect to solar proton events in the future. Figure 1 shows that the sunspot number for the 22nd Schwabe cycle (1986–1996) attained one of its highest values in the historic record and that there was no indication of an approaching Gleissberg minimum in the sunspot number that was comparable to earlier minima. This may support the suggestion of *Lean et al.* [1992] that the Sun is entering a phase similar to the "Grand Maximum" of 1050–1250 A.D. [*Eddy*, 1976]. The consequences of this possibility for solar proton event occurrence are difficult to predict. Thus the very low frequency of occurrence of large fluence solar proton events for the period from 1970 suggests that the highest values of sunspot number may be associated with a factor that reduces the frequency of large fluence solar proton events at Earth, and this is discussed in section 6. The uncertainties in the physics will only be resolved once solar-generated nitrate events have been measured for the Grand Maximum, using the procedure described by *McCracken et al.* [this issue].

Satellite engineering practice uses the SPE and related solar-terrestrial characteristics for solar cycles 20–22 to determine engineering and commercial risk in addition to operational lifetimes. A return to the high solar proton event rates observed at the maxima of the Gleissberg periodicity shown in Figure 2 would have substantial impact on space engineering and space travel.

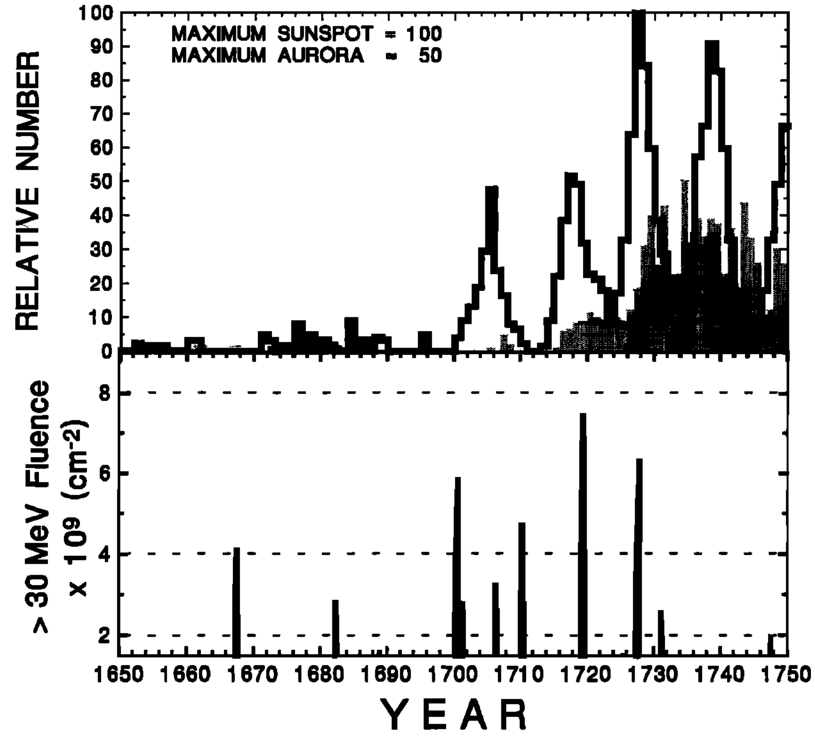

Figure 3. Sunspot, aurorae, and solar proton event activity in the period 1650–1750, illustrating the phase lags between the phenomena at the end of the Maunder Minimum. For clarity of presentation the maximum sunspot numbers from the National Geophysical Data Center are normalized to 100 (solid dark line); the aurorae data (gray shading) from *Eddy* [1976] are normalized to 50.

4. End of the Maunder Minimum

In the following, we examine a feature of the solar proton event data that may provide insight into the varying conditions in the inner solar system during the Gleissberg cycle. Figure 3 displays the international sunspot number [*McKinnon*, 1987; *National Geophysical Data Center*, 2000] and aurorae occurrence [*Eddy*, 1976, 1977] between 1650 and 1750. The solar proton event distribution for the same period is also shown.

Since the pioneering work of Eddy, there has been a concerted international effort to recover "lost" sunspot observations prior to and during the Maunder Minima [*Letfus*, 1993, 1999; *Hoyt and Schatten*, 1995a, 1995b, 1996]. There has been a renormalization of these early observations into the criteria for the international sunspot number [*Hoyt and Shatten*, 1992, 1995c, 1995d, 1998a, 1998b], and these are the sunspot numbers plotted in the figures in this paper. These numbers are available from the *National Geophysical Data Center* [2000].

The abrupt increase in aurorae circa 1715 led Eddy to conclude that the Maunder Minimum ended in 1715. Quoting the work of *Eddy* [1976, 1977], this date has been accepted by many scientists. Certainly, the aurorae data make it clear that the major break with the past behavior of the geomagnetic field did not occur until 1715–1716.

Consider, now, the renormalized international sunspot numbers together with the solar proton events having >30 MeV fluences $>2.0 \times 10^9$ cm^{-2}. These data are displayed in Figure 3. From Table 1 of *McCracken et al.* [this issue] we find four large solar proton events observed in the nitrate record during Schwabe cycle 1698–1711 (i.e., in 1700, 1701, 1706, and 1710). Table 1 shows that this cycle was one of the four cycles yielding the highest number of solar proton events in the nitrate record between 1561 and 1950. Thus, in the 15 years prior to 1715, four large fluence solar proton events were identified compared to three in the 16-year period thereafter.

The observed annual frequency of large fluence solar proton events derived from the nitrate record was 0.04 yr^{-1} during the period 1650–1699. (Note that the following discussion does not use normalized proton event occurrence.) Testing the hypothesis that the solar conditions during the period 1700–1715 were identical to those during 1650–1699, we compute that the probability that four solar proton events would occur in 15 years is 2.2×10^{-3}. This low probability indicates that the physical conditions changed abruptly in the vicinity of 1700. While aurorae apparently did not "switch on" until about 1715, the switch on in large fluence solar proton event occurrence above the very low frequency of the Maunder Minimum occurred 15 years earlier. Figure 3 also shows that there were few SPE after 1735, at which time the aurorae were just reaching a plateau, which persisted until ~1750. These results imply that there was a phase lag of approximately 15 years between the commencement of solar proton events and the onset of geomagnetic activity.

The SPE data, together with the estimates of the international sunspot number shown in Figure 1 indicate that the Sun had commenced to develop substantial magnetic fields during 1700–1715, leading to particle acceleration processes similar to those occurring in modern times. However, the paucity of aurorae during those years (with implication of a paucity of geomagnetic storms) further implies either (1) that few interplanetary shock waves reached Earth, or (2) the absence of strong southward directed B_z fields interacting with the magnetosphere.

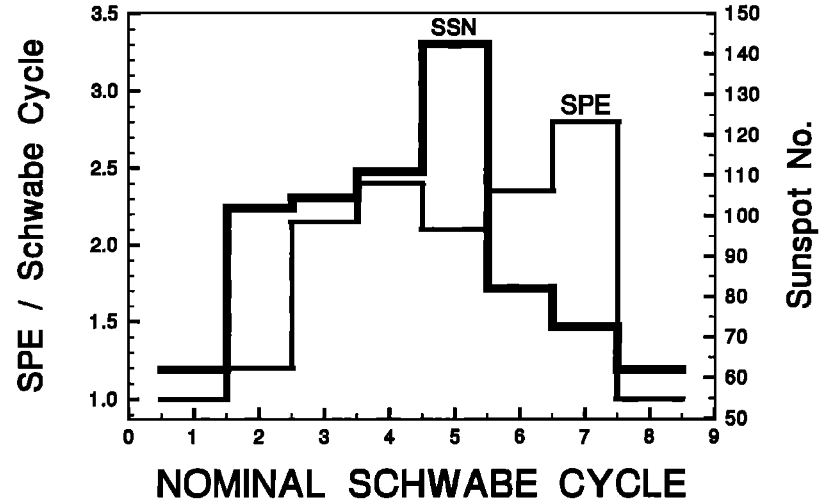

Figure 4. The variation in solar proton event frequency and peak sunspot number (SSN) throughout the sunspot Gleissberg cycle. The data are averaged over the two sunspot Gleissberg cycles 1750–1830 and 1830–1910. Each data point corresponds to the average of the two Schwabe cycles at that phase in the Gleissberg cycle. A linear detrend has been applied.

In section 6 we interpret the delay between the solar proton event and aurorae onsets to be associated with changes in the solar corona and conclude that the sunspot and solar proton event data indicate that the Maunder Minimum as expressed in solar properties ended about 1700. Similar conclusions have been reached previously by *Schove* [1979, 1983].

5. Solar Proton Event Frequency Throughout the Gleissberg Cycle

Figure 4 displays the frequency of occurrence of large fluence solar proton events and the sunspot number as a function of time, averaged over the two Gleissberg cycles 1750–1830 and 1830–1910. Each data point corresponds to the average of the two Schwabe cycles at that phase in the Gleissberg cycle. The absence of reliable sunspot numbers for earlier Gleissberg cycles precluded their initial use, and the Gleissberg cycle after 1910 was not included since it is not clear that this cycle has reached completion.

Examination of Figure 4 shows that the variation of the sunspot number is broadly symmetric about the midpoint of the Gleissberg cycle, as can be seen in the individual sunspot Gleissberg cycles displayed in Figure 1. By way of contrast, the frequency of occurrence of large fluence solar proton events appears to increase in an approximately monotonic manner to a maximum late in the Gleissberg cycle. Identifying the Maunder Minimum as the first half of the preceding sunspot Gleissberg cycle (i.e., 1660–1750), the same bias toward SPE activity late in the Gleissberg cycle is evident.

In view of the small numbers of large fluence solar proton events in each Schwabe cycle, and the limited scope of the result (three Gleissberg cycles at best), this result must be viewed with caution. Until it can be tested over a longer time series of SPE data, we regard it as a simple experimental result that there was a skewed distribution of SPE occurrence in the last half of the three consecutive Gleissberg cycles 1650–1910. We note that this behavior does not appear to have occurred in the Gleissberg cycle 1910–1985?; however, the fact that the international sunspot number had not commenced to decline up to the end of the 22nd Schwabe cycle indicates that other factors may be operating.

6. Role of the Corona

Eddy [1976, 1977] and *Parker* [1975] have discussed the fact that eclipse observations indicate that the solar corona was almost invisible at the end of the Maunder Minimum and that the first observation of coronal streamers occurred in 1716. (See description of observation by R. Cotes given by *Eddy* [1976].) These authors suggest that the whole sun was essentially a "coronal hole" at the end of the Maunder Minimum. This would imply a considerably faster, less dense solar wind, and the paucity of sunspots suggests that the magnetic field entrained in the solar wind may have been considerably weaker than in the modern era. The low inferred *K* coronal intensities [*Eddy*, 1976] suggest that the matter density in the corona may have been one or more orders of magnitude less than in our present experience.

Further, the corona is known to change greatly between the minimum and maximum of the Schwabe cycle. It is to be expected that there would be similar quantitative changes between the minima and maxima of the Gleissberg cycle. For example, *Lockwood et al.* [1999] have reported that the Sun's coronal field has increased by a factor of 2.3 since 1901 (i.e., since the 1910 minimum of the Gleissberg periodicity). Consider therefore a model summarized by Table 3. In this table both Gleissberg columns refer to the maxima of the Schwabe cycles at that phase of the Gleissberg cycle.

We suggest the following model which is based on the "coronal mass ejection acceleration model" of Reames and others [cf. *Reames*, 1995, 1999]. We do this because many of the large fluence solar proton events in the nitrate and satellite records since the commencement of magnetic recording in the mid 1800s were accompanied by exceptional geomagnetic storms. Thus the Carrington event in 1859, those of 1909 and 1928, February 1942, July 1946, November 1960, and August 1972 were all associated with major magnetic storms, resulting from solar activity near central meridian [*Carrington*, 1860; *Cliver et*

Table 3. Phenomenological Model of Coronal Properties and Their Consequences Throughout the Gleissberg Cycle

Solar and Interplanetary Features	Maunder Minimum	Gleissberg Minimum (e.g., 1910)	Gleissberg Maximum (e.g., 1860)
Coronal matter density	very low	low	high
Coronal magnetic field	low	higher	X2 higher
Coronal mass ejection velocity	high	medium	low
Solar proton acceleration	very efficient	efficient	less efficient
Interplanetary shock	weak	strong	strong

al., 1990a, 1990b; *Shea et al.*, 1999]. There are two events in the recent nitrate record that are the consequence of activity on the western limb of the Sun (i.e., February 1956 and September 1989). However, these events are not the results of coronal mass ejections (CMEs) directed toward the Earth and are not associated with exceptionally large fluences at the Earth. Furthermore, previous studies have shown that solar proton events associated with solar activity near central meridian that result in fast coronal mass ejections have fluences that are usually up to an order of magnitude greater than those associated with fast CMEs from western limb solar activity [*Shea and Smart*, 1993, 1996; *Reames*, 1999].

For the model summarized in Table 3 the matter and magnetic densities are lowest in the Maunder Minimum, somewhat higher in the other minima of Gleissberg cycles and highest near the maxima of a Gleissberg cycle. As a consequence, even a small CME at the end of the Maunder Minimum would meet little resistance from the surrounding coronal medium, and the ejection velocity would be high. It has been shown that the efficiency of solar proton acceleration by a CME varies as the fourth power of the CME velocity [*Reames*, 2000]; as a consequence acceleration would be particularly effective during and immediately after the Maunder Minimum. Furthermore, the low particle and magnetic density in interplanetary space would mean that the shock wave generated by the CME would have a considerably smaller momentum density than in the present era, and there would be minor geomagnetic activity when it reached Earth. These predictions are consistent with the data summarized in Figure 3 illustrating the paucity of aurorae prior to ~1715.

On the basis of this model, efficient propagation of shock waves to the orbit of Earth would not occur until there had been enough solar activity to increase the coronal and interplanetary matter and magnetic density, through the development of coronal streamers, and an extended corona. As noted above, clear evidence of the development of the corona was not reported until 1716, at which time the upsurge in aurorae indicates that geomagnetic storms had commenced 15 years after the commencement of large fluence solar proton events and a large increase in the sunspot number.

The model implies that CMEs near the maximum of the Gleissberg cycle would encounter the greatest resistance from the matter and magnetic densities. As a consequence, the average ejection velocities would be lower, and because of the fourth power law of velocity [*Reames*, 2000], particle acceleration would be less efficient. This prediction is consistent with the absence of large solar proton events after 1735, near the peak of the Gleissberg cycle from 1650–1750. The kinetic energy of the CME will probably increase as the maximum of the Gleissberg cycle is approached, and this can be expected to compensate to some degree for the increased coronal matter densities. However, the model would be interpreted to indicate that this was insufficient to compensate for the higher coronal density in the vicinity of 1735 as proposed by the model.

Through the declining phase of the Gleissberg cycle, the model indicates that the matter and magnetic densities of the corona would slowly decline. As a result, the CME ejection velocities could be higher and the particle acceleration increasingly efficient. Approaching the minimum of the Gleissberg cycle, CMEs would achieve higher ejection velocities, and particle acceleration would become more efficient. This is consistent with the data in Figure 1 prior to the Gleissberg minima of 1820 and 1910, and the tendency to skewness noted in Figure 4. In particular, the model predicts that provided that there was sufficient magnetic activity on the Sun to generate CMEs, the frequency of occurrence of solar proton events could be at a maximum immediately prior to and during the sunspot Gleissberg minima. Reference to Figure 1 shows that this was the case for the sunspot Gleissberg minima circa 1820 and 1910. On the basis of this model the relative absence of solar proton events during the Maunder Minimum would be due to the virtual absence of coronal mass ejections at that time.

In summary, our phenomenological model accounts for the early "turn on" of large fluence solar proton events after the Maunder Minimum and the delayed onset of geomagnetic activity. The model is also in accord with the higher frequency of large fluence solar proton events during the declining phase and minima of several Gleissberg cycles. Examination of eclipse and magnetic records, in conjunction with the SPE data for the period 1880–1920 will assist in validating this model, and further extending our understanding of the extent to which coronal changes are associated with the time variability of solar proton events. This, in turn, will allow the long-term changes in the solar wind, and the modulation of the galactic cosmic radiation to be investigated.

7. Maximum Fluence for a Solar Proton Event and the Streaming Limit for Solar Proton Event Fluence

In the modern epoch the highest estimated >30 MeV proton fluence was 9.0×10^9 cm^{-2} for the event of November 12, 1960 [*Shea and Smart*, 1990]. For engineering and other purposes the sequence of events August 2–7, 1972, with a >30 MeV proton fluence of 5×10^9 cm^{-2} [*Shea and Smart*, 1990] is taken as the maximum credible fluence.

Reference to Table 1 of *McCracken et al.* [this issue] indicates that the fluence associated with the Carrington white light flare is estimated to be 18.8×10^9 cm^{-2}. As discussed in section 8 of *McCracken et al.* [this issue], this estimate was based upon a value of 40 for the conversion factor, $K(t, \lambda)$, which was regarded as a conservative estimate for the entire data series. However, the Carrington event occurred on September 1, 1859, and the late summer precipitation process was probably less efficient than is implied by a conversion factor of 40. Taking the event of August 1972 as a better approximation to the precipitation of nitrate in the polar summer, Table 3 of *McCracken et al.* [this issue] shows that a value of 20 for $K(t, \lambda)$ would be more appropriate. This implies that the >30 MeV fluence of the Carrington event could have been about 36 × 10^9 cm^{-2}. Thus the two estimates indicate that the fluence for the September 1859 solar proton event was between 4 and 8 times greater than the August 1972 solar proton event.

Reames [1999] has summarized the work that has lead to the recognition that the intensities of solar proton events associated with "gradual" solar X-ray activity exhibit an asymptotic value of particle flux due to interaction between resonant ion waves and the SPE fluxes, yielding streaming limited particle fluxes early in a solar proton event. This process should also set a limit for the fluence in a very large event, and we now test whether the Carrington event, and other large SPEs in the nitrate record have approached or exceeded that limit. We take the event of October 19, 1989, with a >30 MeV omnidirectional fluence of 4.2×10^9 cm^{-2} as a model of a large event. This is the largest >30 MeV fluence solar proton event in the 22nd Schwabe cycle [*Smart and Shea*, 1997]. We then assume the streaming limited time profile of 4 MeV can be extrapolated to 30 MeV in an even larger event, an assumption suggested by *Reames* [1999]. Now, assuming that the fluxes associated with the shock itself are, as in the case of the October 19, 1989, event, a factor of 100 greater than the streaming limited fluxes, we compute the streaming limited omnidirectional >30 MeV fluence for a very large SPE to be 8×10^9 cm^{-2}.

Figure 5 of *McCracken et al.* [this issue] illustrates the cumulative normalized probabilities for large solar proton events, as measured by both spacecraft and by the nitrate record. As can be seen in this figure, there is a major reduction in probability of occurrence of SPEs with fluences at and above the vicinity of 6×10^9 cm^{-2}. In view of the approximate agreement with our estimate, we speculate that this feature of Figure 5 of *McCracken et al.* [this issue] is indicative of streaming limitations on the fluences above about 8×10^9 cm^{-2}. Although the Carrington solar proton event and several others in Figure 1 indicate that fluences greater than our estimate of the streaming limited fluences do occur, the cumulative probability curve suggests that the streaming limit is effective about $6-8 \times 10^9$ cm^{-2} for fluences of >30 MeV protons.

Figure 1 of this present paper and Table 1 of *McCracken et al.* [this issue] indicate that there were five events in the interval 1561–1950 that equal or exceed our 8×10^9 cm^{-2} estimate of the streaming limited >30 MeV fluence. Of these there are good magnetic and solar records for the Carrington solar proton event of 1859 and the events of 1895 and 1896. Close examination of these collateral data should be profitable. It is beyond the scope of this paper to do this, other than to note that the interplanetary medium may have been particularly disturbed at these three times or that there may have been two completely independent SPEs within our "resolution time" of about 6 weeks. There were several well-documented magnetic storms at the time of the Carrington event, one with an exceptionally fast transit time of 17.1 hours [*Cliver et al.*, 1990a, 1990b]. The year 1894 contained eight of the "Great Geomagnetic Storms" 1874–1952 as identified by the *Royal Greenwich Observatory* [1955]; thus the 13th Schwabe cycle (1889–1901) appears to have been a time of substantial magnetic disturbance. As a consequence, these three events with fluences at or above our estimate of the maximum streaming limited fluence may be due to the superposition or interaction of several acceleration events within the 6 weeks resolution time of the nitrate data. We propose that these events deserve more careful study. If superposition or interaction can be shown to have been likely, it will even more firmly establish the streaming limit for fluence to be in the vicinity of $6-8 \times 10^9$ cm^{-2} for >30 MeV protons per event. Nevertheless, the possibility that a solar proton episode can achieve a >30 MeV fluence of 18–36 × 10^9 cm^{-2} has substantial implications for human space flight and satellite engineering.

8. Solar Proton Event Occurrence as an Index of Solar Activity

The sunspot number is commonly used as an index of solar disturbance, in large part due to the fact that it has been possible to extrapolate it with some certainty to the middle of the 18th century [*Eddy*, 1976]. It has been shown to be a useful index to understand the time dependence of many interplanetary and terrestrial phenomena, and it itself has provided a clear insight into the short-term (<100 years) variability of the Sun [e.g., *Sonett et al.*, 1997].

However, the shortness of the sunspot record has prevented definitive study of longer-term variations in the properties of the Sun. For example, testing the suggestion that the solar dynamo is intermittent [*Weiss*, 1994], and investigation of whether the longer periodicities (e.g., 210 and 2300 years) observed in ^{14}C are of solar or orbital origin [*Sonett et al.*, 1997], require reliable solar data over a timescale of 10,000 years or more.

A similar difficulty is encountered in the validation and study of longer-term solar effects upon terrestrial phenomena, where those data themselves are noisy and contain more than one source of variability. Thus the validation of solar control on the ^{14}C in the Earth's atmosphere, in the presence of the low-pass filtering effects of the Earth's biosphere and oceans, and changes in the Earth's magnetic dipole, has been difficult and has relied on fragmentary records of sunspots and aurorae [e.g., *Stuiver and Quay*, 1980]. Likewise, the demonstration of solar control of climatic variables such as the eustatic sea level in the presence of isostatic rebound (mechanical hysterisis of the Earth's crust) is contentious due to the fragmentary nature of solar data over time scales of >400 years [*Fairbridge*, 1967]. Without an independent index of solar activity, it is unlikely that unambiguous validation of solar control beyond 1000 years into the past will be possible.

For the above reasons, the ability to quantify solar activity through the identification of solar proton events in polar ice cores has significance far beyond the study of the events themselves. As stated in section 11 of *McCracken et al.* [this issue], drill holes extending into ice that is 40,000 years old are common, while there have been two drill holes extending into ice more than 200,000 years old [*Legrand and Mayewski*, 1997]. Since the nitrate is securely trapped in the crystals of consolidated ice and there are no known decay mechanisms, it is feasible to consider the identification of solar proton events extending far into the past. We can therefore anticipate using the impulsive nitrate events to study solar activity and solar magnetic properties over a period of time that is up to 100 times the length available to us today.

There will be a similar impact upon the study of solar control on the heliosphere and the terrestrial environment. There have been a number of studies that have indicated a correlation between sunspot number and the climate of Earth [*Fairbridge*, 1967; *Eddy*, 1976, 1977]. It has been proposed that the "little ice ages" were associated with the Spoerer and Maunder Minima, and that there was a "Grand Sunspot Maximum," 1100–1250 A.D., that correlated with a warm climate in Europe. It has been argued that the cloud cover of the polar regions is positively correlated with the galactic cosmic radiation [*Svensmark and Friis-Christensen*, 1997], thereby defining a possible mechanism whereby the Sun can influence climate. Verification of these hypotheses has been impossible due to the uncertain knowledge of solar activity prior to 1700. The rate of occurrence of SPE, acting as a proxy for solar activity as indicated in Figure 4, together with the measurements of the galactic cosmic radiation provided by ^{10}Be and ^{14}C, will now allow these hypotheses to be tested over a much greater period than has been possible previously.

In summary, it is appropriate to think of the Sun and the heliosphere as a tightly coupled physical system, with transfer functions, and feedback paths that have time constants ranging from days to millennia and longer. To date, ^{10}Be, ^{14}C, and world climate have been the only system outputs that are available for the past 30,000 years (for ^{14}C) and >100,000 years (for ^{10}Be). However, these have been outputs that occurred toward the output end of the total heliospheric system, and we have had no knowledge of the concurrent solar activity that was driving the system. With the impulsive nitrate measurements of SPEs we have identified, for the first time, a semiquantitative monitor of the solar activity that has driven the heliospheric system for thousands of years in the past.

Examination of Figure 2 shows that while the solar proton event frequency and sunspot number curves show some similarities, they are not identical. This is further demonstrated by comparison of the second, third, and fifth columns in Table 2. Thus we note that (1) while the average peak sunspot numbers for the third and fourth Gleissberg cycles are almost equal, both of the SPE parameters (columns 3 and 5) for the fourth Gleissberg cycle are almost twice those for the third cycle, and (2) in Figure 2 the SPE frequency drops monotonically from 1950 to one of the lowest values in the 433 years of SPE data, while over the same time the sunspot number has attained the highest values in the whole sunspot record.

The production of ^{14}C is considered to be a maximum when the galactic cosmic radiation flux is at a maximum. This has occurred, in our cosmic radiation instrumentation era, at sunspot minimum. Figure 2 includes the ^{14}C production rates as computed by *Stuiver and Quay* [1980]. Interpreting it as a plot of the galactic cosmic radiation versus time, a similar disparity is noted as above. Thus the high solar proton event frequency for the fourth Gleissberg cycle (1830–1910) is not reflected in deeper modulation than in the third.

Our knowledge of the Sun is sufficiently detailed that such differences are not unexpected, and their study can be expected to further our state of knowledge (see section 6). As a semiquantitative indicator of enhanced solar activity for use in the analysis of other phenomena, the ability to extend it far into the past is expected to be much more important than the apparent differences between the large fluence solar proton event frequency and sunspot number.

9. Conclusions

Analysis of the characteristics of the nitrate events 1561–1950, and ionospheric and the satellite measurements 1950–1994, has provided the following information about solar-terrestrial phenomena.

1. The normalized frequency of occurrence of large fluence solar proton events has varied by a factor of 15 from 0.5 to 8 per Schwabe cycle.
2. The period of satellite measurement (1964–1996) has had a low normalized frequency of large fluence solar proton event occurrence (one event/Schwabe cycle) compared to up to 8/cycle observed during the periods circa 1610, 1710, 1790, 1870, and 1950.
3. The frequency of occurrence of large solar proton events exhibits an approximate 80–85 year (Gleissberg) periodicity previously recognized in sunspot numbers. Six minima of the Gleissberg periodicity are evident in the SPE data, two being closely associated with the Maunder and Dalton Minima in the sunspot numbers. It is concluded that the satellite era of observations has coincided with the recurrence of this series of Gleissberg minima in SPE frequency.
4. The five largest solar proton events in a Schwabe cycle provide a sensitive indicator of the cumulative probability of all the solar proton events for that cycle.
5. The Gleissberg period 1820–1910 was the most prolific generator of solar proton events followed by the period 1580–1660. The present Gleissberg period (1910–1985?) is one of the least effective in large fluence solar proton events observed at Earth.
6. The resumption of solar proton event activity after the Maunder Minimum occurred 16 years prior to the generally accepted end of the minimum, as gauged from aurorae and solar observations. The statistical probability of this occurring by chance is small, and we conclude that this is a real effect, indicative of the solar or heliospheric conditions at the time. Thus the Maunder Minimum in solar phenomena ended about 1700 and not 1715–1716.
7. The occurrence of solar proton events is shown to have been skewed to the declining phase of the three sunspot Gleissberg cycles 1660–1910.
8. The largest SPE in the nitrate record, and associated with the Carrington white light flare, had a >30 MeV proton fluence that was in the range 18–36 × 10^9 cm^{-2}. This is a factor of 4–8 times greater than the value for the August 1972 event, which has frequently been regarded as the "worst case" solar proton event.

From the results derived in this paper we (1) propose a phenomenological model, wherein variations in the properties of the solar corona account for the delayed switch on of aurorae after the Maunder Minimum and the tendency for the SPE frequency to increase during the declining phase of the sunspot Gleissberg cycle. We (2) estimate that the streaming limited fluence for >30 MeV protons is 8 × 10^9 cm^{-2} and speculate that the break in slope in the cumulative probability distribution in the vicinity of 6 × 10^9 cm^{-2} in Figure 5 of *McCracken et al.* [this issue] is indicative of this effect. This suggests that the Carrington SPE of 1859 is an example of a solar proton event that exceeded the streaming limit, and therefore worthy of careful study using the magnetic and other data from that time. We (3) predict that the frequency of large solar proton events may increase from its present low value by a factor of 6 to 8 commencing perhaps in the next Schwabe cycle. Should this prediction be correct, the Earth will experience substantially more solar proton events and ground level events than has been our experience during the period since 1950. This will have major implications for space flight and engineering.

This paper demonstrates that nitrate events in polar ice core have the potential to provide a means of studying the occurrence of solar proton events and solar activity far into the past. This will provide the ability to investigate long-term changes in the temporal characteristics of the dynamo processes that generate the variable solar magnetic fields and to investigate any links that may exist between solar activity and climate change during recent geological time. With the impulsive nitrate measurements of SPE we have, for the first time, the ability to monitor the solar activity that has driven the whole heliospheric system for many thousands of years into the past.

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G. A. M. Dreschhoff, Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045. (giselad@ku.edu)

K. G. McCracken, Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742-2431, USA. (jellore@hinet.net.au)

M. A. Shea and D. F. Smart, Air Force Research Laboratory, Space Vehicles Directorate, 29 Randolph Road, Hanscom AFB, Bedford, MA 01731-3010. (sssrc@msn.com; sssrc@msn.com)

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