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Solar proton events for 450 years: The Carrington event in perspective

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Abstract

Using high resolution measurements of the impulsive nitrate events in polar ice as identifiers of solar proton events in the past, we have identified 19 events over the period 1561–1950 that equal or exceed the >30 MeV fluence measured during the August 1972 episode of solar proton events. The largest nitrate impulsive deposition event (and largest solar proton fluence above 30 MeV) occurred in late 1859 in time association with the Carrington flare of September 1859. The Carrington flare occurred near the central meridian of the sun; the interplanetary disturbance associated with the solar activity rapidly traveled toward the earth resulting in an extremely large geomagnetic storm commencing within 17.1 h of the visual observation of the solar flare. While this event was remarkable by itself, historical records indicate that the Carrington event was part of a sequence of solar activity as an active region traversed the solar disk. We compare the derived omni-directional solar proton fluence for the Carrington event of 1.9×10^{10} cm^{-2} above 30 MeV with the solar proton fluence from the past and from more recent episodes of solar activity. The Carrington event is the largest solar proton event identified in our ~450 year period, having almost twice the >30 MeV solar proton fluence than the second largest event in 1895, and approximately four times the solar proton fluence of the August 1972 events.

Keywords: Carrington event; Solar proton events; Solar proton event comparisons

1. Introduction

Over the past 15 years ongoing studies have shown that impulsive nitrate events in polar ice provide an historical record of major solar proton fluence events. The initial work on this relationship was pioneered by Zeller et al. (1986) and Dreschhoff and Zeller (1990) with the identification of large spikes in nitrate concentration present in a "super clean[1] " ice core drilled at Windless Bight, Antarctica (78°S, 167°E). This core was analyzed at ultra high resolution (1.5 cm intervals). When the dating of the ice core was completed, it was apparent that many of the spikes coincided with the time of major solar proton events and/or major solar flare activity. The ultra high resolution analysis of a second core drilled at Windless Bight in 1991 verified the results of the first core. The composite results of the two cores are illustrated in Fig. 1. The two ice cores from Antarctica acquired on the Ross ice shelf only cover a time period extending back to ~1900. Inspection of Fig. 1 indicates a correspondence between the impulsive nitrate spikes and the large solar proton events observed by spacecraft since the 1970s. Shea et al. (1993, 1999) provided the initial association of these large nitrate deposition events

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[1] In normal ice core drilling, the drill bit is lubricated with a mixture of ethylene glycol and diesel fuel to prevent freezing. The diesel fuel contains nitrates that result in contamination when the objective is nitrate detection at the nanogram level.

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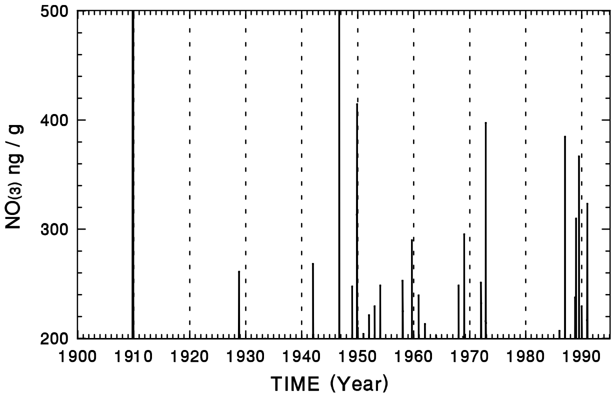

Fig. 1. Measurements of nitrate concentration from ice cores drilled at Windless Bight, Antarctica. The dating of the nitrate precipitation is given on the *X*-axis; the *Y*-axis indicates the nitrate concentration in nanograms of nitrate per gram of water. There is a significant amount of "noise" in this data record, probably due to terresterial weather, so the data display threshold has been set to 200 nanograms of nitrate per gram of water.

with known large solar proton events or outstanding solar-terrestrial events. However, some of the spikes did not correlate with solar proton events and seem to be associated, in part, with meteorological events (Dreschhoff and Zeller, 1990).

Fig. 2 illustrates the impulsive nitrate deposition event at Windless Bight in 1946. This impulsive event corresponds to the July 1946 ground-level event measured by the Cheltenham ionization chamber (Forbush, 1946) and shown in Fig. 3. This high-energy solar proton event, associated with solar activity on the central meridian of the sun, was followed by a sudden commencement geomagnetic disturbance approximately 26 h later. Cosmic ray ionization detectors have been in operation since 1935; these instruments measure cosmic radiation with energies above ~4 GeV. It was not until ~1949 that the more sensitive cosmic ray neutron monitors were developed. A sea level neutron monitor in high and polar latitudes records the secondary neutrons generated by the primary cosmic radiation above ~450 MeV. Since proxies for solar proton events were not developed until the 19th solar cycle (1954–1965) and since routine spacecraft measurements were not available until late 1965, solar proton flux and fluence measurements below ~450 MeV were not available prior to the 19th solar cycle.

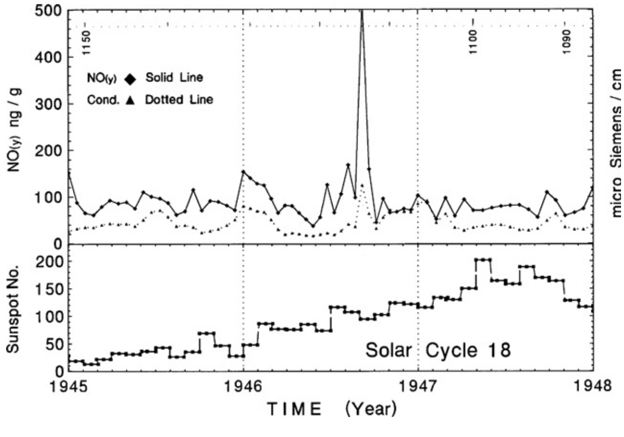

Fig. 2. The impulsive nitrate deposition event at Windless Bight, Antarctica corresponding to the July 1946 ground-level solar cosmic ray event. The black line shows the NOy deposition. The light dotted line indicates the electrical conductivity used to identify volcanic eruption time markers. The sample number in the ice core is indicated at the top of the figure. The monthly sunspot number for this period of solar cycle 18 is indicated at the bottom of the figure. We have evaluated the >30 MeV solar proton fluence for this event as 6.0×10^9 cm^{-2} (McCracken et al., 2001a; Smart et al., 2006).

2. The solar proton–NOy chain

A one-to-one correspondence has been demonstrated between the seven largest solar proton fluence events that have been observed since continuous recording of the cosmic radiation started in 1936 and the corresponding thin nitrate layers. The probability of this occurring by chance was computed to be $<10^{-6}$ (McCracken et al., 2001a). The ionizing solar protons penetrating deep into the polar atmosphere create secondary electrons that dissociate molecular nitrogen and generate "odd nitrogen", a generic term for a complex of nitrate radicals designated by the symbol NOy. (The NOy consists of N, NO, NO_2, NO_3, HN_2O_5, N_2O_5, HNO_3, HO_2NO_2, $ClONO_2$ and $BrONO_2$.) The chemical recombination reactions in the Earth's upper atmosphere generating the nitrate radicals and subsequent ozone depletion are complex (Jackman et al., 1990, 1995) and a detailed description is beyond the scope of this paper. Jackman and McPeters (2004) have detailed the probable NOy generation and consequent ozone reduction effects for the large fluence solar proton events observed in the "space measurement era" since 1969. Some of the produced HNO_3 becomes attached to aerosols which, by gravitational sedimentation, are transported downwards into the troposphere and are precipitated into the polar ice within an ~6-week time period. Since the nitrate deposition in polar ice occurs over a specific time period, we used the total fluence for an episode of activity such as the multiple of events in August 1972 and October 1989. Details of the verification of the nature of the nitrate events, and the calibration technique including allowances made for seasonal variations and ice density are given by McCracken et al. (2001a). Comparison of the nitrate data, and the estimates of energetic proton fluence based on satellite and other data, provided a conversion relationship that allows the proton fluence to be estimated from the nitrate data.

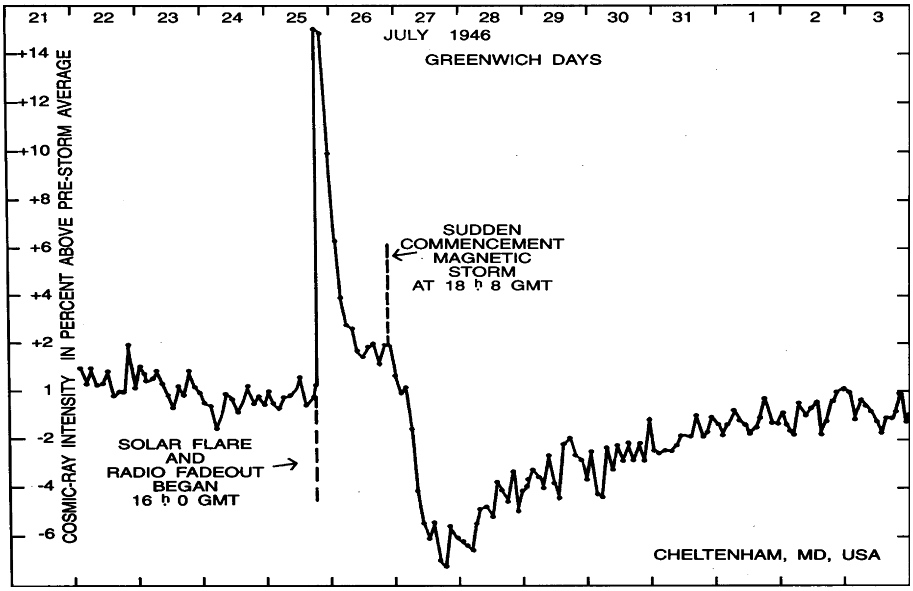

Fig. 3. The July 1946 ground-level cosmic ray event as measured by the ionization chamber in Cheltenham, Maryland, USA. The associated solar activity occurred at 10°E (Forbush, 1946). Ionization chambers detect solar protons having energies above ~4 GeV.

3. Validation of the nitrate data and the solar proton fluence calibration

In 1992 an ice core 125.6 m in length (named GISP2-H) was obtained using "super clean" drilling techniques) at Summit, Greenland (72°N, 38°W), specifically for ultra-high resolution nitrate studies. This deep interior polar location is removed from the coast and fluctuations in nitrate concentration of meteorological origin such as wind erosion are minimal. In addition, the available meteorological data indicate that this site in central Greenland has approximately uniform precipitation throughout the year as compared to the more southern or northern locations in the ice sheet (Bromwich et al., 1999). Dating of this 125.6-m core established that the precipitation was deposited in the years between 1561 and 1992, whereas the two firn[2] cores from Antarctica acquired on the Ross Ice Shelf only cover a time period extending back to ~1900. Comparing the nitrate measurements from the three cores, it became evident that there was a seasonal dependence between the two polar regions. The Antarctic meteorological polar vortex is most prevalent during the austral winter; nitrates from solar proton events in July–September/October should precipitate relatively rapidly into the Antarctic polar ice.

An exhaustive study of the GISP2-H ice core, in combination with the two Antarctic cores, eliminated most of the uncertainties in the association between the impulsive nitrate events and the production of cosmic radiation by the Sun (McCracken et al., 2001a,b). It demonstrated that the impulsive nitrate events have a characteristic short time-scale (<~6 weeks) and are highly correlated with periods of major solar-terrestrial disturbances, the probability of chance correlation being $<10^{-9}$.

Subsequent analysis has demonstrated that there is a strong inverse correlation between the probability of occurrence of solar proton events recorded in the nitrate data, and the estimated strength of the interplanetary magnetic field (McCracken et al., 2004). This experimental result is in accord with the theoretical understanding of the acceleration of energetic protons in strong interplanetary shocks. Together, the above studies have provided a strong basis for the conclusion that the impulsive nitrate events are causally related to the generation of energetic protons by solar activity. On the basis of that conclusion the nitrate data are used here to estimate the energetic proton fluences associated with the Carrington event.

To aid in the following discussion, we summarize some of the key features of the nitrate data as established by McCracken et al. (2001a). Using the derived calibration between nitrate concentration and solar proton events, the initial analysis of the GISP2-H core resulted in the identification of 70 impulsive nitrate enhancements with a >30 MeV omni-directional fluence $\geqslant 2 \times 10^9\ \mathrm{cm}^{-2}$ for the period 1561–1950 (McCracken et al., 2001a). This fluence threshold was selected because these impulsive nitrate events were five standard deviations above the background level, and excludes the fluctuations in nitrate concentration that may be of meteorological origin at this deep interior location.

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[2] Firn is a glaciology term that describes the polar snow not yet consolidated into ice.

- Seventy impulsive nitrate events were identified in the 389-year interval, 1561–1950, with an estimated >30 MeV omni-directional proton fluence of $\geqslant 2 \times 10^9\ \text{cm}^{-2}$.
- The date of occurrence of the impulsive nitrate events has been estimated using the annual wave in the concentration of nitrate in polar ice, and the occurrence of enhanced electrical conductivity due to well-dated volcanic eruptions. Errors in the year assigned to an impulsive nitrate event are estimated to be ±1 year in the absence of a well-defined volcanic eruption within ~5 years of the impulsive event.
- The power spectra of the fluctuations in the nitrate data indicated that the "noisiness" of the nitrate data decreased by a factor of three between those based on unconsolidated "firn" (1960–1989) and consolidated ice (pre 1900).
- The largest impulsive event in the 389-year record occurred in the boreal autumn of 1859. Well-dated volcanic eruptions occurred in 1853 and 1854, and there was a well-defined annual variation in the nitrate data between 1853 and 1862, providing confidence that the impulsive event did occur in 1859.

4. Solar proton fluence and geomagnetic disturbances

From the analysis of solar proton events in solar cycles 19–22 (April 1954 to September 1996) we know that the largest solar proton fluence events are those associated with solar activity at the central meridian of the sun (Shea and Smart, 1996; Smart and Shea, 2003). When there is a fast interplanetary shock wave, the impact of the shock with the magnetosphere usually results in a geomagnetic disturbance, typically within 20–30 h after the "parent" solar activity. The combination of the initial solar proton flux and the additional flux accelerated by the interplanetary shock can give rise to an extremely large solar proton event lasting for several days, and which often peaks when the interplanetary shock wave passes the Earth (Reames, 1999). This process can occur up to the lower relativistic energies recorded by the cosmic ray neutron monitors. When there is a very active solar region traversing the solar disk, a multiplicity of solar flares, fast coronal mass ejections and interplanetary shocks can generate major disturbances at the earth that are often accompanied by observations of mid and low latitude aurora. Examples in recent times are the events of August 1972, October 1989 and October 2003.

NOy is also generated in the high atmosphere by the ionization produced by the auroral electrons, but at a much greater height, ~80 km. This high altitude NOy production is unlikely to survive photo disassociations and be transported to the troposphere. We find a poor general correlation between auroral activity and impulsive NOy events. The associations that have been found (Shea and Smart, 2004) are with outstanding solar-terrestrial events, indicating a common solar source that results in very large proton fluences, severe geomagnetic storms and low-latitude aurora.

Table 1 lists the solar proton events from 1950–2003 where the >30 MeV omni directional solar proton fluence exceeds $2 \times 10^9\ \text{cm}^{-2}$. The fluence values are from Shea and Smart (1990) and Smart and Shea (2002), supplemented by our analysis of the GOES solar proton data. For events with a sequence of activity, it is often difficult to determine the fluence associated with each individual coronal mass ejection/solar flare. We have listed the start of each event and summed the proton flux throughout the entire sequence of activity. Since the results from the nitrate measurements represent the total period throughout a sequence of activity such as in October 1989, spacecraft and ground-based measurements over a sequence of activity must be combined for a valid comparison. Thus the derived fluence of $1.0 \times 10^9\ \text{cm}^{-2}$ measured for the event on 11 July 1959 has been combined with the derived fluence of $1.3 \times 10^9\ \text{cm}^{-2}$ for the event on 14 July 1959 for a total

Table 1
Solar proton events between 1950 and 2004 with > 30 MeV fluence $>2 \times 10^9\ \text{cm}^{-2}$

Solar cycle	Cycle start	Event start	>30 MeV fluence	G Mag storm	Sequence of activity
19	1954.3	11 Jul 1959	2.3×10^9	G, CM	Yes
19	1954.3	12 Nov 1960	9.0×10^9	G, CM	Yes
20	1964.9	4 Aug 1972	5.0×10^9	G, CM	Yes
22	1986.8	19 Oct 1989	4.3×10^9	G, CM	Yes
23	1996.8	14 Jul 2000	4.3×10^9	G, CM	Yes
23	1996.8	9 Nov 2000	3.1×10^9	No	No
23	1996.8	4 Nov 2001	3.4×10^9	G, CM	No
23	1996.8	28 Oct 2003	3.3×10^9	G, CM	Yes

Notes:
G, major geomagnetic storm associated with solar proton event.
CM, sunspot region near central meridian of the sun.
Yes, a sequence of activity as the active region crossed the solar disk.

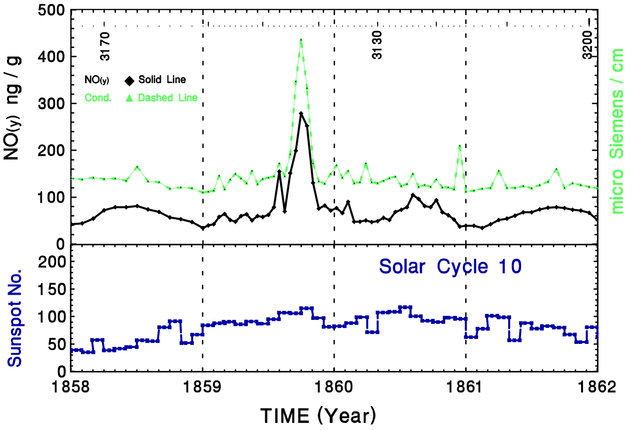

Fig. 4. The impulsive NOy deposition event in Greenland polar ice that corresponds to the Carrington event of 1 September 1859. The black line shows the NOy deposition. The light line indicates the electrical conductivity used to identify volcanic eruption time markers. (It also responds to the HNO_3 produced by solar protons – see text.) The sample number in the ice core is indicated at the top of the figure. The monthly sunspot number for this period of solar cycle 10 is indicated at the bottom of the figure.

derived fluence of 2.3×10^9 cm^{-2} in a comparison of fluences deduced from the nitrate measurements.

Reames (1999) has shown that there is a self-limiting process that limits the proton intensity, and hence the fluence, to a maximum value; this is called the "streaming limit". Of the 70 events in the catalogue of nitrate events, three exceed the "streaming limit" by a significant amount, one being the event in Fig. 4. McCracken et al. (2001b) have proposed that this may be due to (a) the superposition of separate events; or (b) the interaction of several interplanetary shock waves due to separate coronal mass ejections, as will be discussed further below.

5. The Carrington event, 1 September 1859

The impulsive nitrate deposition event associated with the September 1859 "Carrington" flare is shown in Fig. 4. This increase has been evaluated with a >30 MeV omni-directional solar proton fluence of 1.88×10^{10} cm^{-2}. From many historical records (e.g., Royal Greenwich Observatory, 1955; Akademie der Wissenschaften, 1861; Kimball, 1960; Heis, 1859; Loomis, 1859, 1860a,b,c,d) we know that there was a major geomagnetic storm with a sudden commencement at 7.5 UT on 28 August; aurora were observed at many mid and low latitude locations. The second major geomagnetic storm of this period started with a sudden commencement at 4.7 UT on 2 September 1859 with aurora observed at latitudes as low as Honolulu, Hawaii. The second geomagnetic storm has been associated with the visual observation of a solar flare made by Carrington (1860) and Hodgson (1860) on 1 September 1859.

From these records we assume that both geomagnetic storms were part of a sequence of solar activity, probably from the same active region on the sun. Modern experience indicates that several shock waves would have been in transit to and past the Earth. The solar flare observed by Carrington was located at 12°W. The Carrington region would have been at ~50°E on 27 August 1859, and while a major geomagnetic storm associated with solar activity from a region 50°E of central meridian is relatively rare, there are reports of similar associations since 1950. Our modern experience therefore suggests strongly that the solar proton flux associated with the Carrington "event" was from a sequence of solar flares, fast coronal mass ejections and interplanetary shocks.

A "precursor" impulsive spike is evident in Fig. 4; this is immediately before the large increase that we associate with the Carrington event of September 1859. There are no known solar flare sightings prior to the 1 September 1859 event; however, 1859 contained several periods of geomagnetic activity and mid-latitude auroral observations. Mid-latitude auroral observations were recorded on 21–23 and 28–29 April 1859 (Křivský and Pejml, 1988); geomagnetic disturbances were recorded on 21, 22 and 29 April 1859 (Ellis, 1900; Akademie der Wissenschaften, 1861). In July there was a large magnetic needle variation event recorded in Austria (Akademie der Wissenschaften, 1861). It is probable that these events contributed to the precursor spike in the nitrate data that evaluates as an omni directional >30 MeV fluence of 2.9×10^9 cm^{-2}.

6. Comparison of the Carrington solar proton fluence with other solar proton events

From the analysis of the GISP2-H ice core, we have identified 70 impulsive nitrate events that have been evaluated to have a >30 MeV solar proton fluence above 2×10^9 cm^{-2} for the period 1561–1950 (McCracken et al., 2001a). Using ground-based and satellite measurements, there are eight similar large fluence events from 1950–2003. The first major large solar proton fluence event that was recorded by spacecraft occurred during August 1972, and it is this event against which most comparisons are made.

From our nitrate measurements of ice cores we have identified 19 solar proton events having a >30 MeV omni-directional fluence greater or equal to the fluence measured during the August 1972 events. (This is probably an underestimate by about 25%, for reasons given in McCracken et al., 2001a). These events are listed in chronological order in Table 2 together with information on related phenomena such as geomagnetic disturbances, and auroral observations. From our knowledge of present events, we know that the majority of large

Table 2
Solar proton events between 1570 and 1950 as identified from impulsive nitrate enhancements in Polar ice

Solar cycle	Cycle start	Event date	Rank	>30 MeV fluence	G Mag storm	Mid-lat aurora	Sequence of activity
		1603.6	18	5.2×10^9		Kr	
		1605.7	8	7.1×10^9		Kr	
−11	1619.0	1619.6	5	8.0×10^9			
−10	1634.0	1637.7	12	6.1×10^9		Kr	P
−9	1645.0	1647.9	17	5.2×10^9			
−4	1698.0	1700.8	14	5.8×10^9			
−3	1712.0	1719.5	7	7.4×10^9		Kr	P
−2	1723.5	1727.9	11	6.3×10^9		Kr, Yau	P
1	1755.2	1756.0	16	5.4×10^9			
4	1784.7	1793.6	15	5.5×10^9		Kr	
6	1810.6	1813.2	10	6.4×10^9		Kr	
9	1843.5	1851.8	3	9.3×10^9	G, CM	Kr	P
10	1856.0	1859.8	1	18.8×10^9	G, CM	Kr	Yes
10	1856.0	1864.8	9	7.0×10^9	G	Kr	
11	1867.2	1878.6	19	5.0×10^9	G, CM	Kr	P
13	1889.6	1894.9	6	7.7×10^9	G, CM	Kr	Yes
13	1889.6	1895.7	2	11.1×10^9	G, CM	Kr	P
13	1889.6	1896.7	4	8.0×10^9	G, CM	Kr	Yes
18	1944.2	1946.5	13	6.0×10^9	G, CM	Sil	

All events have >30 MeV Fluence $\geqslant 5\times10^9$ cm^{-2}.
Notation:
G, geomagnetic Storm within a three-month period prior to the nitrate enhancement.
CM, sunspot region observed near central meridian.
Kr, data from Křivský and Pejml (1988).
Yau, data from Yau et al. (1995).
Sil, data from Silverman (2002).
P, possible sequence of solar activity.
Yes, known sequence of solar activity.
The event of 1946.5 in the 18th solar cycle is from the Antarctic ice core; all other events are from the GISP2-H core drilled at Summit, Greenland.

solar proton fluence events are associated with solar activity near the central meridian of the sun. From the Royal Greenwich Observatory (1950) records, we have identified geomagnetic storms and/or aurora that occurred within a three-month period prior to the maximum of the impulsive nitrate deposition enhancements between 1840 and 1950. From the auroral records of Křivský and Pejml (1988) and Yau et al. (1995) we have also identified periods when mid or low latitude aurora were observed. Observations of mid and low latitude aurora over a several day period were considered to be possible episodes of solar activity.

From Tables 1 and 2 we note that the Carrington event has the largest solar proton fluence >30 MeV from 1561 to the present. The second largest event occurred in 1895 during a solar cycle that had three very large solar proton events. These events exceed the streaming limit (two marginally); it is possible that they are associated with a multiplicity of shock waves in space from a sequence of solar activity.

7. Summary

We have compared the >30 MeV solar proton fluence deduced from impulsive nitrate deposition events in polar ice extending back to 1561 with modern day ground-based and satellite measurements. Using an omni-directional fluence of 5×10^9 cm^{-2} measured during the August 1972 events as a fiducal mark, we have identified 19 solar proton events between 1561 and 1950 having fluence equal or greater than the August 1972 event. There were five such events in the 18th century (1700–1799), and eight events in the 19th century (1800-1899). There was one event in the first half of the 20th century (1946) and two events in the “modern instrumentation” era (1960 and 1972). The majority of the large fluence solar proton events appear to be associated with solar activity near the central meridian of the sun, often with multiple coronal mass ejections and multiple interplanetary shocks. The Carrington event is, by far, the largest solar proton event identified in our ~450 year period, having almost twice the >30 MeV solar proton fluence than the second largest event in 1895, and approximately four times the solar proton fluence of the August 1972 event.

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