Multiple Evidence of Intense Solar Proton Events During Solar Cycle 13

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Abstract

We present evidence of intense solar proton events in the last decade of the XIX century based on diverse solar and geophysical data. One of those events (July 15, 1892) was observed by George Hale as a 'remarkable solar disturbance'. There appears to be a number of intense solar flare events at that period concurrent with solar cycle 13. Besides white-light flares, there were more numerous storm sudden commencements (SSC) of high amplitude ($>$ 40 nT), noticeable enhanced annual sums of the Aa^* index, more frequent observation of very bright *aurorae borealis* in North America. This phenomenon is also revealed from data on nitrates in polar ice and cosmogenic isotopes in terrestrial archives.

1 Introduction

1.1. Production of ^{14}C by galactic and solar cosmic rays. Cosmic rays upon entering the atmosphere produce spallation reactions with atmospheric components, primarily N, O and Ar. These spallation reactions initiate nuclear cascades producing fast neutrons. About 2/3 of the fast neutrons are thermalized without reacting and become available to produce ^{14}C by the reaction ^{14}N(n,p)^{14}C. The ^{14}C is oxidized to CO_2 and enters the carbon cycle eventually being distributed within the biospheric and oceanic reservoirs as well as the atmospheric reservoir. The distribution of radiocarbon in nature is controlled by a balance between processes of production, radioactive decay (T1/2= 5730 yrs) and exchange between reservoirs, which can be described by a system of linear differential equations. Some of the reservoir components are well stratified, consisting of annual layers, for example, annual tree rings, coral rings, lake varves and polar ice. By measuring year by year the relative abundance of ^{14}C in each annual layer, one can determine the radiocarbon production rate and, consequently, the cosmic ray intensity as a function of time.

Temporal variations of the galactic cosmic rays (GCR) incident on the Earth's atmosphere result from changes in the intensity of the heliomagnetic and geomagnetic fields that modulate the production of ^{14}C and other cosmogenic isotopes (Damon & Sonett, 1991; Stuiver & Braziunas, 1993). Changes in the geomagnetic field dominate the atmospheric ^{14}C/^{12}C ratio that, as a result, varied by $\pm 50^\circ/_{\circ\circ}$ during the last ten millennia (Holocene). Superimposed on the trend produced by changes in the geomagnetic field intensity, there is a fine structure (Damon et al., 1989) caused by the longer period variations of solar activity: ca. 2200-yr, 210-yr and 88-yr cycles. Because the atmosphere contains about 100 times as much ^{14}C as the annual production of ^{14}C, the carbon cycle acts as a low pass filter with greater attenuation at higher frequencies. The higher frequencies, e.g. the Schwabe cycle (ca. 11 yr) produce a hyperfine structure (ibid.). Variations due to fine structure of the radiocarbon spectrum cause a variation of about $\pm 15^\circ/_{\circ\circ}$ whereas the hyperfine structure, e.g., the Schwabe cycle results in a variation of about $\pm 2^\circ/_{\circ\circ}$. It is commonly assumed that fine structure, at $\pm 2^\circ/_{\circ\circ}$ measurement precision, consists of the 11-yr cycle and 'noise'. Recent work has shown otherwise, for example, we have retrieved a ^{14}C signal probably produced by nucleonic cascades initiated by the hard gamma-rays from supernova SN1006 (Damon et al., 1995a; Damon et al., 1995b).

1.2. Solar cosmic ray observations.

Solar cosmic rays (SCR) are mostly protons emitted by the Sun and accelerated during solar flares that occur more frequently in the active phases of solar activity. Their energy depends on flare intensity and may lie in the range from approximately several hundreds of keV per nucleon up to about several tens of GeV. The maximum energy E_m for the flare on February 23, 1956 was 19 GeV per nucleon, for December 26, 1982 - 11 GeV. For the flare on September 29, 1989 Miroshnichenko (1992) estimated proton E_m up to TeV. Due to such high energies they can penetrate to altitudes of 20-30 km in the Earth's atmosphere (Maeda, 1965) and can be detected as Ground Level Events (GLE). This penetration is especially strong near the poles, where low-energy protons of 5 to 20 MeV can enter the Earth's atmosphere and are usually detected as a Polar Cap Absorption (PCA). It has been established by observations that solar proton events (SPE) can be detected on the Earth within a few hours after flare eruption and may last for less than 1 day to more than 5 days, depending on the severity of the event. Energetic solar protons also produce ^{14}C.

2 Evidence for High Solar Flare Activity During Solar Cycle 13

Evidence for high solar flare activity during solar cycle 13 (from minimum at AD 1867.2 to minimum at AD 1901.7 (McKinnon, 1987)) is presented in Figure 1 as discussed below.

2.1. Solar flares (optical, white light). On July 15, 1892 George Hale reported ”a remarkable solar disturbance” (Hale, 1892; Hale, 1931). It appeared as a large and active sunspot. It was also manifested by ”the occurrence of a terrestrial magnetic storm about nineteen and a half hours after the beginning of the solar eruption and a much more violent storm about five hours later”. George Hale had observed a white solar flare. Another white flare was observed in 1891 and an earlier white flare event had occurred in 1872 (Neidig & Cliver, 1983). 28 years elapsed before another white flare occurred in 1921 during the Contemporaneous Solar Maximum (CSM) (Jirikowic & Damon, 1994). Ten white light solar flares were observed during the CSM from 1921 to 1950 **(Fig.1,A)**.

2.2. Aurora borealis (northern lights). We used an available catalog of aurora observations done at the Blue Hill Meteorological Observatory (Stetson & Brooks, 1941). During that time, because of the importance of the relationship between auroras and solar activity and also with other geophysical phenomena, aurorae observations were an important component of meteorological observations at the Observatory. The total list includes 280 auroras observations conducted from June 1885 through December 31, 1940. The advantage of the catalog versus other historic catalogs is in its semiquantitative classification of events. The grades used were 0 for faint aurora, 1 for aurora of medium brightness and 2 or 2+ for brilliant aurora. Upon inspecting annual frequency of auroral events of magnitude 2 and 2+ there were 11 events in 1892 compared to a mean rate of less than 2 **(Fig.1,B)**. More than two events rate was reached in 1888, 1893, 1894 and 1896. Only one year reached the level of 6 events, 1939 which was the year before the Blue Hill Observatory discontinued the auroral observations.

2.3. Storm sudden commencements (SSC). We used a list of *storm sudden commencements* (SSC) comprising 2462 events observed from 1868 to 1967 (Mayaud, 1973). **Figure 1,C** shows annual numbers of events of magnitude equal or higher than 40 nT. If all events were shown, the annual frequency would be very similar to that of the annual sunspot number. However, for events of magnitude range 30–39 nT, the annual rate reaches the level of 10 events per year in the 1870's, 1890's, 1930's and 1940's. We chose to plot the events of magnitude higher than 40 nT, because it demonstrates that events of high magnitude do peak in 1892 and do not occur in that annual rate at any other time. Only the year 1946 reaches the level of 10 events which is exceeded by 1892.

2.4. Aa-index. The *Aa* index was suggested and thoroughly elaborated by P.N.Mayaud (Mayaud, 1973) to extend existing series of geomagnetic indices before 1884 (Mayaud, 1980). Indication of geomagnetic storms can be determined by enhancement of index value above 60 (Allen, personal communication). Enhancement above the level of 60 gives one an index called Aa^*. We used a list of 1024 events covering the time interval from 1868 through 1967 (Mayaud, 1973) and calculated annual sums of Aa^* **(Fig.1,D)**. This provides a good measure of frequency of intense solar disturbanes each year. Note that the Aa^*-sum magnitude for 1892 is not exceeded during the CSM.

2.5. Nitrates in polar ice. Concentration of nitrates in polar ice can be used as good indicators of solar protons generated by solar flares within the Earth's atmosphere. Solar protons provide the ionization energy for synthesis of nitrates. Those events are manifested in records of measurements as peaks of extremely short duration less than one year exceeding in magnitude the distinctive seasonal variations. We used data on nitrate concentration in Greenland ice core from the GISP2 drill site at Summit (Zeller & Dreschhoff, 1995). The dates of peaks were calibrated using data on electrical conductivity of ice for the same sequence of samples. Volcanic events yield sulfates into the atmosphere that produce a conductivity signal in ice. When the historical age of a volcanic event is known, it aides in verification of the nitrate time scale. Peaks that were selected of the magnitude higher than 2σ manifest a tendency to cluster in the 1892–1894 time interval **(Fig.1,E)**.

2.6. Radiocarbon. The data on $\Delta^{14}C$ in annual rings of trees from the North American continent (Stuiver et al., 1998) were used for comparison with solar and geophysical records. To extract the solar-flare signal from radiocarbon variations we need first to remove the component due to GCR modulation. The procedure is based on a method used previously (Damon et al., 1989). This requires an approximation of the dependence of the ^{14}C production rate in the Earth's atmosphere on the level of solar activity during the 11-yr (Schwabe) cycle. The mechanism by which the solar wind modulates ^{14}C production is based on the interaction of the GCR with the solar wind plasma and its imbedded magnetic field and random magnetic inhomogeneities. Essentially, the intensity of the GCR undergoes continuous variations in antiphase with solar activity. The radiocarbon generation rate in time Q(t) can be expressed as a first approximation with sufficient accuracy for our purpose as a linear function of the Wolf sunspot number S(t): $Q(t) = Q_0 - C_Q \cdot S(t)$ where C_Q is a coefficient of linear regression (Stuiver & Quay, 1980; Damon et al., 1983).

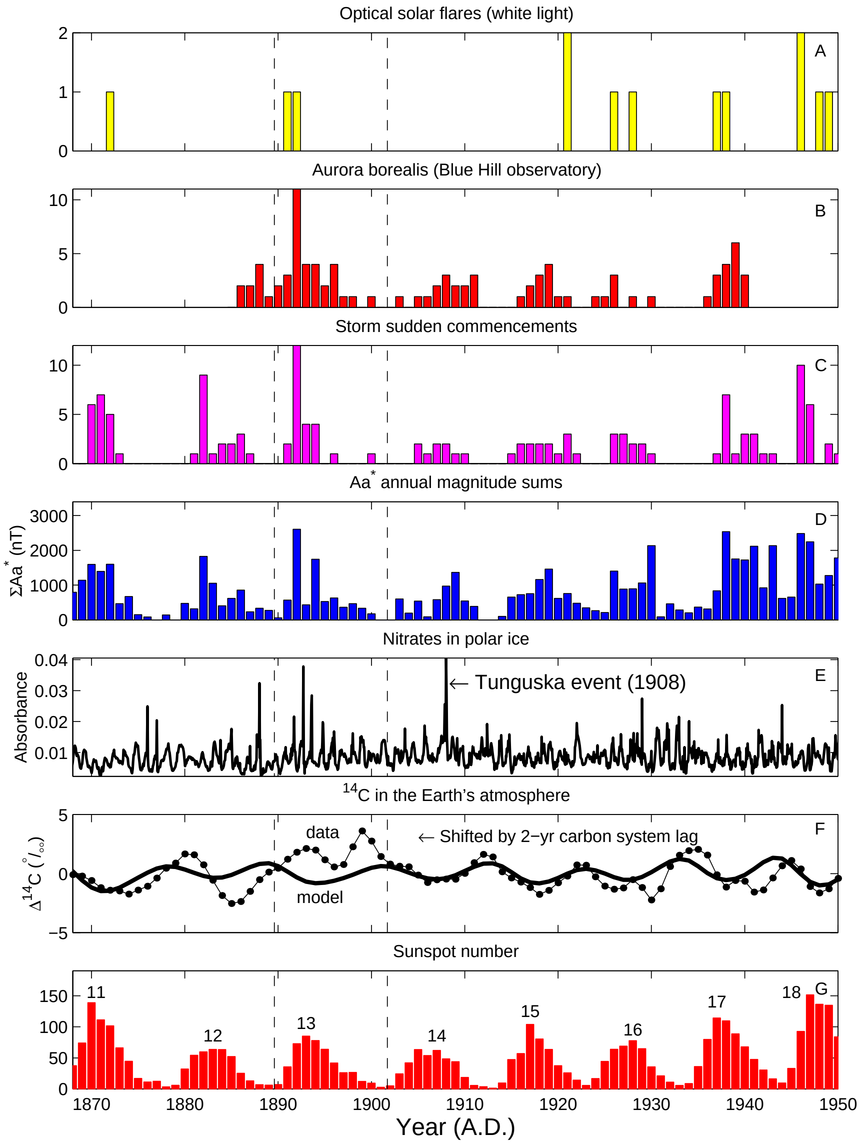

Figure 1:

The production rate in the Earth's atmosphere is distributed between the stratosphere and the troposphere in the proportion of ca 2/3 to 1/3 (Lal & Peters, 1967). We use the above linear regression equation with coefficients determined from the values of Q calculated by Castagnoli and Lal (Castagnoli & Lal, 1980; Damon & Sternberg, 1989) for the solar minimum at 1965 and maximum at 1969 (2.66 and 2.12 $at \cdot cm^{-2} \cdot sec^{-1}$) and corresponding values of the Wolf sunspot number 15.1 and 105.5 (McKinnon, 1987). Hence, the constants are: $Q_0 = 2.75$ and $C_Q = 0.00597$. Here we confine our study to the period from 1868 to 1950 where other data were available for comparison.

The resultant function of Q(t) restored from the sunspot number series for the time period from AD 1700 to the present was entered as input into a computer model of the biogeochemical cycle of carbon to calculate radiocarbon variations in reservoirs of the system and, specifically, in the troposphere. For simulation of the carbon exchange system we use the 6-box model by Bacastow and Keeling (Bacastow & Keeling, 1973), consisting of stratosphere, troposphere, short-lived and long-lived biota, mixed sea layer and deep ocean, with updated parameters and added sedimentary sink. This model of carbon dynamics is accurate enough in its frequency response to approximate satisfactorily the real dynamic characteristics of the Earth's carbon cycle for the processes under investigation.

The resultant series for the time period AD 1868-1950 are depicted in **Figure 1,F**. The comparison shows good agreement between the signal calculated from the Wolf sunspot number as a proxy of the forcing of the carbon cycle model by the solar wind and that derived directly from the experimental data. Besides the discrepancy due to experimental error (1.0–2.5°/$_{\circ\circ}$ in the raw data and suppressed largely by our spline-smoothing), there are obviously additional components in the $\Delta^{14}C$ signal other than the 11-yr cycle. One of these components appears to be produced by solar activity during solar cycle 13.

3 Conclusion

Although solar activity as indicated by the Wolf sunspot numbers is not particularly intense during the solar cycle 13 (with a maximum of 85), it appears to be a time when several very intense solar flares occurred. One of these is George Hale's "remarkable solar disturbance" on July 15, 1982. Various indicators in Figure 1 confirm that intense solar disturbances occur during a cycle when overall solar activity is moderate.

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