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Advances in Space Research 38 (2006) 215–225
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
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# The Carrington event: Possible solar proton intensity–time profile

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Received 9 November 2004; received in revised form 5 April 2005; accepted 5 April 2005

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**Abstract**

A possible >30 MeV solar proton intensity–time profile associated with the Carrington solar flare event of 1 September 1859 is constructed. The derived profile is consistent with a >30 MeV proton omni-directional fluence of $1.9 \times 10^{10}$ cm$^{-2}$ found by the analysis of solar proton generated NOy radicals that are deposited in polar ice. The intensity–time profile of the solar particle flux is constructed by assuming that the Carrington solar event is part of the class of interplanetary shock-dominated events where the maximum particle flux is observed as the shock passes the Earth. This assumption is based on the knowledge that the very large solar proton fluence events (those with >30 MeV omni-directional fluence exceeding $1.0 \times 10^9$ cm$^{-2}$) associated with central meridian solar activity during the last 50 years belong to this class of event. The absence of a statistically significant increase in the observed concentration of the cosmogenic nuclide $^{10}$Be for 1859 indicates that the solar cosmic radiation produced in the Carrington event had a soft spectrum, similar to other interplanetary shock-dominated events.

*Keywords:* Carrington event; Solar protons; Protons intensity; Proton time profile

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## 1. Introduction

### 1.1. Characteristics of large fluence solar proton events observed during the "space era"

When the very large fluence solar proton events observed during the "space era" (1965 to present) are organized by the helio-longitude of the associated solar active region, we find a distinct bi-modal distribution as illustrated in Fig. 1. The events identified in this figure have a >30 MeV omni-directional fluence exceeding $1 \times 10^9$ cm$^{-2}$ as measured by spacecraft at 1 AU. This bi-modal distribution of the very large fluence events persists as far back in time as we can confidently make the solar flare activity–solar proton event time association.

In this bi-modal distribution, the classic western hemisphere solar activity associated proton events constitute one class of events; we will call these "near-sun injection source events". The second class of events is associated with solar activity near the central meridian of the sun. We will refer to these events as "interplanetary shock dominated events". For this second class of events, a fast interplanetary shock from activity near the central meridian of the sun continuously accelerates ions throughout its entire passage from the sun to the Earth. In this class of event, the maximum flux is observed as the shock passes the observer.

A conceptual illustration of these two classes of solar proton events is given in Fig. 2. For the "near-sun injection source events" there is identifiable solar activity, usually a significant solar flare with an associated fast coronal mass ejection (CME) that is directed in the westward direction as viewed from the Earth. This is illustrated on the right side of Fig. 2. These particles are observable at the Earth as long as there is a good interplanetary magnetic field connection between the particle acceleration region and the Earth. Since the classic

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0273-1177/$30 © 2006 Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/j.asr.2005.04.116

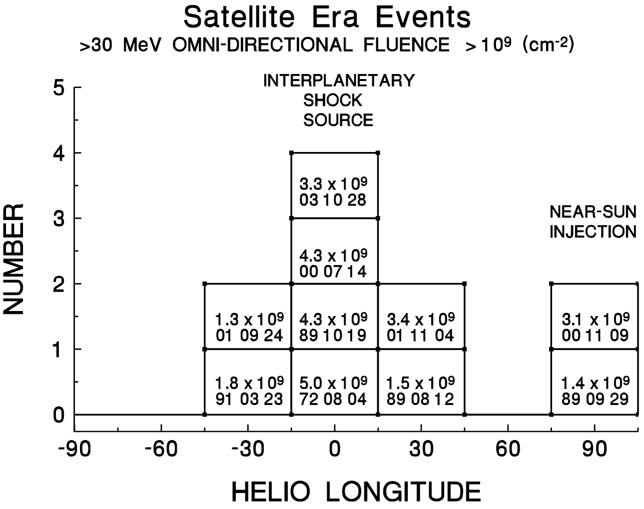

Fig. 1. The helio-longitudinal distribution of very large fluence ($1 \times 10^9$ cm$^{-2}$) >30 MeV solar proton events observed at 1 AU during the spacecraft measurement era (1965-present). The top number in each square indicates the omni-directional fluence; the bottom number indicates the year, month and day of the event. The dates represent either the start of a solar activity episode or the dominant event in a solar activity episode.

Archimedean spiral path from the Sun to the Earth is "rooted" between ~50° and ~90° West helio-longitude (depending on the solar wind speed), the connection to the strong particle acceleration source is relatively brief (due to the fast westward motion of the CME/shock) and consequently, the time of intense particle flux observations at 1 AU is correspondingly brief. There is generally little subsequent associated geomagnetic activity.

For the "interplanetary shock dominated events", the governing feature is a fast broad coronal mass ejection from solar activity near the central meridian of the sun. The fast interplanetary shock forward of this CME continuously accelerates particles as it propagates away from the Sun toward the Earth as illustrated on the left side of Fig. 2. The solar particle fluence at the Earth is the integral of the particles generated by the shock and propagated along the interplanetary magnetic field lines connecting the shock to the Earth. In the eight central meridian events identified in Fig. 1, the maximum flux was observed as the shock passed the Earth-orbiting satellite that acquired the solar proton measurements and this generally corresponded to a major geomagnetic storm commencement.

## 2. Historical large fluence solar proton events

We have searched the published literature to ascertain that the bi-modal distribution shown in Fig. 1 is a systematic effect present in all known large fluence solar proton events. As shown in Fig. 3, this bi-modal pattern does not change when the large solar proton events of the 18th and 19th solar cycles are combined with the events of the spacecraft era. For the events in the 19th solar cycle we used the fluence values from Shea and Smart (1990); for the events in the 18th solar cycle we used the >30 MeV proton fluence derived from the nitrate (NOy) deposits in polar ice (specifically the GISP2-H core from central Greenland) as described by McCracken et al. (2001a). We note that while there are some uncertainties about the magnitude of the solar proton fluence values derived from the NOy deposits, the uncertainties are not significant with respect to the bi-modal distribution.

Solar cosmic ray ground-level events (GLEs) observed as a consequence of solar activity at helio-latitudes >60°W (i.e., in the western member of the bimodal distribution) generally exhibit a significantly harder spectrum

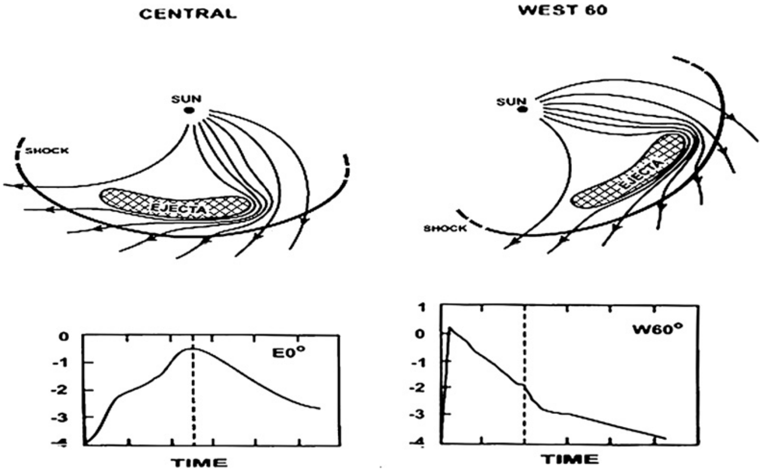

Fig. 2. Conceptual illustration of the two classes of large fluence solar particle events. Upper left: the "interplanetary shock dominated event" results from solar activity near the central meridian of the sun. The CME shock continuously accelerates particles during its transit from the Sun to the Earth. Upper right: the "near-sun injection source event" dominates the observed flux at the Earth only as long as there is a good interplanetary field connection between the accelerating source region and the Earth. The lower panels illustrate typical intensity–time profiles of particles at 1 AU corresponding to each class of event.

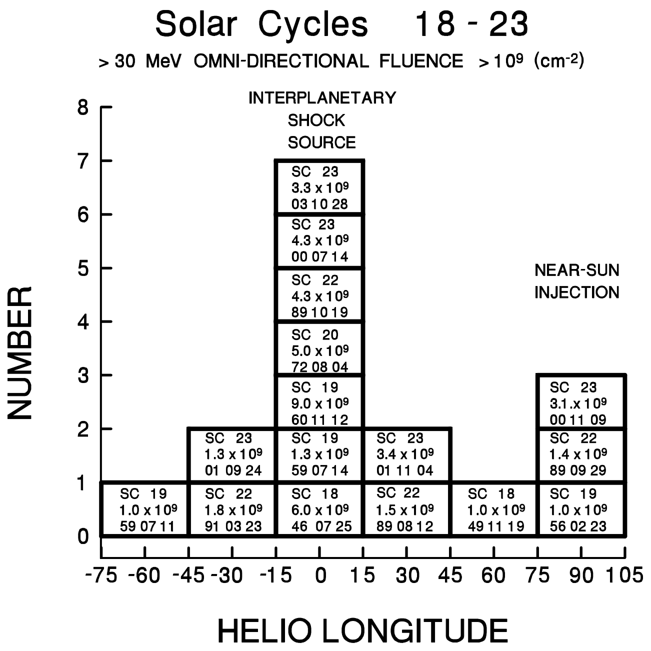

Fig. 3. The helio-longitudinal distribution for all very large fluence ($1 \times 10^9$ cm$^{-2}$) >30 MeV solar proton events observed at 1 AU during solar cycles (SC) 18 through 23. The top number in each square is the solar sunspot cycle number; the middle number in each square indicates the omni-directional fluence. The bottom number in each square is the date of the event. The dates represent either the start of a solar activity episode or the dominant event in a solar activity episode. Solar cycle 18 began in 1944.2; solar cycle 23 began in 1996.8 and is in its late decaying phase in 2005.

than those associated with solar activity near the central meridian. We will use this association later in our study of the characteristics of the Carrington event.

## 3. Evidence for a solar proton event associated with the Carrington event

It is an observational fact that the ozone concentrations in the Earth's polar atmosphere are significantly decreased as a result of large solar proton events (Heath et al., 1977; Jackman et al., 1990). Specific documented events are August 1972 (Heath et al., 1977), the 1989 solar proton events (Jackman et al., 1995), and the July 2000 solar proton event (Jackman et al., 2001). The solar proton ionization in the polar atmosphere creates secondary electrons that dissociate molecular nitrogen and generate "odd nitrogen" (a generic term for a complex of nitrate radicals designated by the symbol NOy) in the polar atmosphere. A highly simplified description is that the nitrate atoms (N) are produced when molecular nitrogen ($N_2$) is dissociated by secondary electrons generated by the ionization energy loss of the incoming energetic protons as they penetrate into the atmosphere. The solar proton produced stratospheric NOy can then be repartitioned fairly rapidly among the family components. 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. (The NOy consists of N, NO, $NO_2$, $NO_3$, $HN_2O_5$, $N_2O_5$, $HNO_3$, $HO_2NO_2$, $ClONO_2$ and $BrONO_2$.) Some of the produced $HNO_3$ is transported to the troposphere, where it is generally precipitated to the surface. Measurements of impulsive nitrate deposition in polar ice are markers of the $HNO_3$ precipitation.

This nitrate radical generation and consequent ozone depletion has been observed for every major solar proton event (>30 MeV fluence $>10^9$ cm$^{-2}$) of the space era. There exists a relatively large background of terrestrial sources of NOy (see Jackman et al., 1980, 1990, 2000), and only very large fluence solar proton events (those with a >30 MeV omni-directional fluence exceeding $\sim 1 \times 10^9$ cm$^{-2}$) will generate sufficient NOy to be observable above this terrestrial background. The experimental evidence from high-resolution sampling of polar ice cores indicates that the deposition of these NOy radicals in polar ice begins ~6 weeks after the initiating solar proton event (Zeller and Dreschhoff, 1995; Dreschhoff and Zeller, 1990, 1998; McCracken et al., 2001a). This association between the impulsive NOy depositions found in polar ice and exceptional solar proton events has been extended back to the beginning of routine cosmic radiation measurements in the 1930s and to exceptional solar–terresterial/major geomagnetic storm events since 1909 (McCracken et al., 2001a; Shea et al., 1999).

Fig. 4 displays the nitrate data corresponding to the interval from 1858–1862, obtained from the GISP2-H

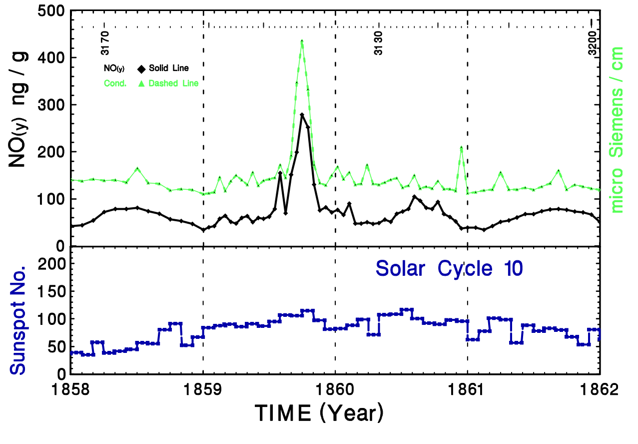

Fig. 4. The impulsive nitrate deposition event in Greenland polar ice that corresponds to the Carrington event of 1 September 1859. The black line shows the nitrate concentration in units of nanograms per gram of water. The light line indicates the electrical conductivity in µS cm$^{-1}$. The monthly sunspot number for this period of solar cycle 10 is indicated at the bottom of the figure. The impulsive increase immediately prior to the largest increase may be associated with an event in July 1859 at which time a large magnetic needle variation was recorded in Austria. See Akademia der Wissenschaften (1861).

ice core acquired at Summit, Greenland (72°N, 38°W) in 1992. The impulsive nitrate deposition event illustrated in this figure (the largest impulsive NOy deposition event in the ice core[1]) is in close time association with the Carrington event in 1859. The section of the GISP2-H core that corresponds to the Carrington event is well dated by the debris in the ice from well known Icelandic volcanoes, which alleviates the ambiguity present in dates assigned to some earlier sections of the core.

On 1 September 1859 Carrington (1860) observed a white light solar flare 12° West of central meridian; 17.5 h later there was a geomagnetic sudden commencement that initiated a major geomagnetic storm. A >30 MeV omni-directional proton fluence of $1.9 \times 10^{10}$ protons $\text{cm}^{-2}$ was derived from the total NOy deposition using procedures detailed in McCracken et al., 2001a. The intense fluence of solar protons inferred from the nitrate data, together with the location of the white light flare, and the subsequent very fast interplanetary shock (indicated by the very strong magnetic disturbance and very large magnetic storm), led us to conclude that this large solar proton event is similar in nature to the solar proton events associated with activity near the central meridian of the sun as identified in Figs. 1 and 3. The evidence suggests that the impulsive nitrate enhancement was the result of an extremely large number of solar protons associated with the very fast interplanetary shock initiated by the Carrington white light event.

Routine observations of solar particle events began in the 19th solar cycle by interpreting polar ionospheric measurements to deduce the probable solar particle flux generating the observed ionospheric effects. Routine measurements of solar proton events from spacecraft commenced in 1965 and continues to the present. The time distribution of the >30 MeV solar proton events from 1954 to 2004 is shown in Fig. 5. The "star" toward the top of the figure represents the >30 MeV solar proton fluence of $1.9 \times 10^{10}$ protons $\text{cm}^{-2}$ deduced for the Carrington event and provides a perspective of the relative magnitude of the solar protons associated with the Carrington event compared with contemporary observations. Examination of this figure shows the Carrington event fluence is at least a factor of 4 higher than any event observed in the "space era".

Table 1 lists selected members of the group of very large omni-directional fluence solar proton events that are associated with central meridian solar activity. There are strong similarities between these ground-level events (GLEs), and we will utilize these similarities to estimate the probable solar proton intensity–time profile for the 1859 event.

Extraordinary solar cosmic ray events are often associated with "white light solar flares", a rare occurrence when the optical emission is of sufficient intensity to be discerned against the photospheric background, indicating that the energy released is greater than in the majority of solar flares. McCracken (1959) showed that the large solar cosmic ray ground-level events of July 1946, November 1949, and February 1956, were all associated with white light solar flares, and suggested this was a direct consequence of the high energy release evidenced by the emission of white light. The November 1960, and August 1972 sequences, which exhibited the highest fluences observed in the "space era", are also associated with white light flares. The events of July 1946 and August 1972 are both associated with white light flares close to the solar central meridian. This association provides confidence that the impulsive event in the nitrate record was causally related to the Carrington white light flare.

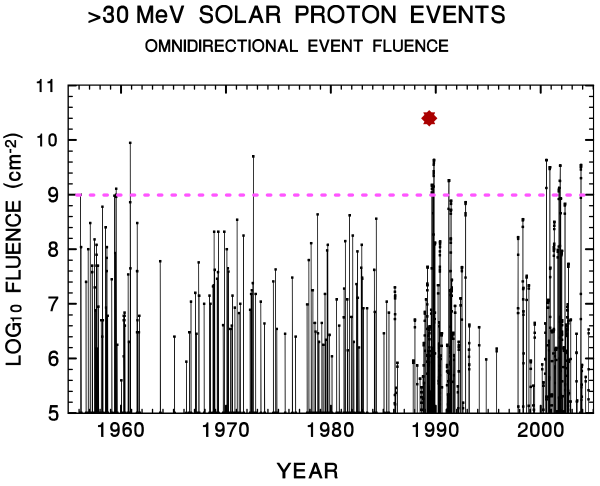

Fig. 5. The >30 MeV solar proton event fluence since the beginning of the 19th solar cycle. The dashed line indicates the detection threshold for NOy events in polar ice. Our omni-directional derived fluence for the Carrington event is indicated by the "Star" at $1.9 \times 10^{10}$ $\text{cm}^{-2}$. The fluence values are from Shea and Smart (1990) supplemented by the GOES spacecraft data.

## 4. Reference events

In our construction of a possible solar proton intensity–time profile for the Carrington event we will rely on the general characteristics of very large fluence events associated with central meridian solar activity for the past 60 years. Specifically we will use the major solar activity and solar proton measurements during July 1946, July 1959, August 1972 and March 1991 for our reference events.

### *4.1. The July 1946 event*

Details concerning the July 1946 event are shown in Figs. 6 and 7. We use this event to demonstrate that a sig-

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[1] The GISP2-H ice core covered the time interval from 1561 to 1992.

Table 1
Very large omni-directional fluence solar proton events associated with central meridian solar activity

| Date | Solar longitude | GLE | >30 MeV peak flux (cm$^2$ s ster)$^{-1}$ | >30 MeV fluence (cm$^{-2}$) |
|---|---|---|---|---|
| 1859 09 01 | W12 (WL) | Probable | $5 \times 10^4$ [a] | $19 \times 10^9$ |
| 1946 07 25 | E10 (WL) | 20% Ion Chamber[b] | No. observations | $6 \times 10^9$ |
| 1959 07 14 | E04 | 10% NM | Riometer Saturation | $2.3 \times 10^9$ |
| 1960 11 12 | W04 | 105% NM | Riometer Saturation | |
| 1960 11 15 | W32 (WL) | 100% NM | Riometer Saturation | $9 \times 10^9$ |
| 1972 08 04 | E08 (WL) | 10% NM | $\sim 2 \times 10^4$ | $5 \times 10^9$ |
| 2003 10 28 | E08 | 14% NM | $4.5 \times 10^3$ | $3.4 \times 10^9$ |

GLE, ground-level enhancement; WL, white light solar flare; NM, sea level neutron monitor 15-min data.

[a] Flux derived in this paper.

[b] Equivalent neutron monitor increases are approximately a factor of ten greater.

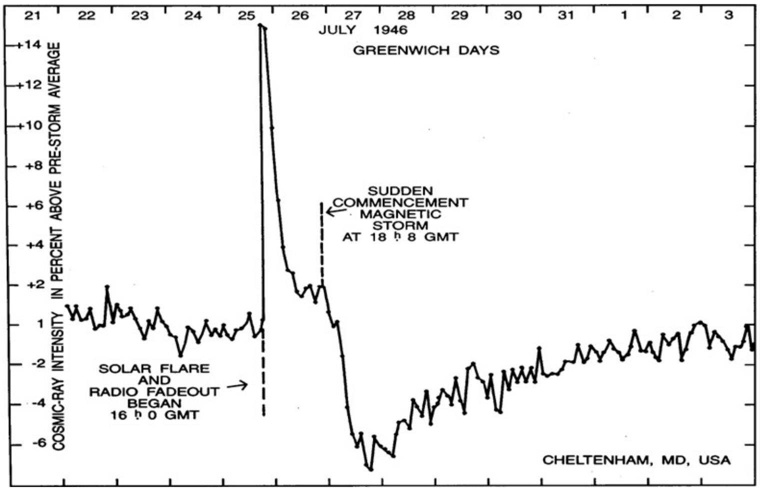

Fig. 6. The July 1946 ground-level cosmic ray event (GLE) as measured by an ionization chamber (Forbush, 1946). The associated white light solar flare occurred at 10° east helio-longitude.

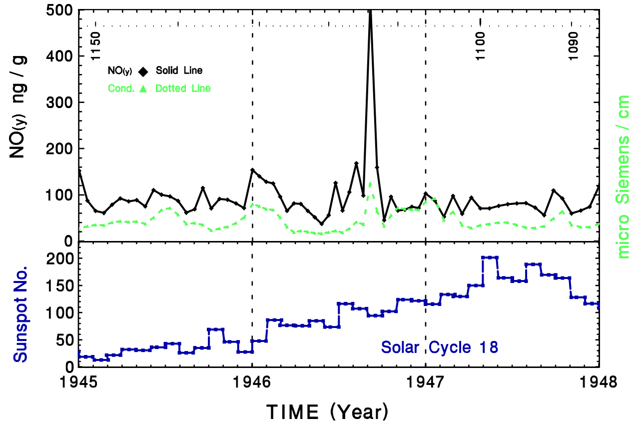

Fig. 7. The impulsive nitrate deposition event in Antarctica that corresponds to the July 1946 GLE. The dark line in the top panel shows the nitrate concentration in units of nanograms per gram of water. The dotted line indicates the electrical conductivity in μS cm$^{-1}$. The sample number in the ice core is indicated at the top of the figure. The monthly sunspot number for this period of solar cycle 18 is at the bottom of the figure. We evaluate the >30 MeV proton fluence for this event as $\sim 6 \times 10^9$ cm$^{-2}$.

nificant GLE can be associated with central meridian solar activity. Fig. 6 illustrates the ground-level cosmic ray enhancement (GLE) as measured by the cosmic ray ionization chamber at Cheltenham, MD, USA (Forbush, 1946). The solar proton detection threshold of an ionization chamber is ~4 GeV. Fig. 7 illustrates the impulsive nitrate deposition for this event from an ice core drilled at Windless Bight, Antarctica (78°S, 167°E). (There is a distinct seasonal effect in the detection efficiency of the recording of NOy events in polar ice. The collection efficiency of solar proton generated NOy events is maximized when the atmospheric polar vortex is present. The July 1946 event is more distinct in the Antarctic ice core than in the Greenland GISP2-H ice core.) Using the calibration factor derived by McCracken et al. (2001a), the July 1946 solar proton event has been evaluated as having a >30 MeV omni-directional solar proton fluence of $6 \times 10^9$ cm$^{-2}$.

### 4.2. The July 1959 solar activity episode

The July 1959 solar activity episode is not as well documented as later events observed with spacecraft, but it provides evidence that far eastern hemisphere solar events can generate very large ($\sim 10^9$ fluence) solar proton events at the Earth. The details of this solar activity episode, a series of $3^+$ solar flares from the same active region with subsequent Earth observed flux maxima coincident with the great geomagnetic storms, are contained in Švestka and Simon (1975). The proton flux from the initial solar event, a 3$^+$ solar flare at 60° east almost reached the $10^9$ omni-directional fluence threshold at energies >30 MeV. The subsequent solar events in this solar activity episode generated a very large composite solar proton fluence event and an outstanding solar–terrestrial event.

### 4.3. The August 1972 solar activity episode

Details concerning the August 1972 episode of solar activity are shown in Figs. 8–10. The associated active region was at 35°E when the solar flare activity episode began. At the time of the major 3B solar flare on 4 August, the active region was at 9°E. (See Fig. 1 for the relative position of this event compared with other "satellite era" large fluence solar proton events.) Fig. 8 illustrates the high-energy solar cosmic ray intensity recorded on 4 August by the neutron monitor at Kiruna, Sweden (solar particle detection threshold of 0.4 GeV). (This 11.5% increase was the largest ground-level increase recorded for this event by a sea level neutron monitor.) Fig. 9 illustrates the impulsive nitrate deposition for this event as measured from the Windless Bight, Antarctica (78°S, 167°E) ice core. Fig. 10 presents our analysis of >30 and >60 MeV solar proton data for this solar activity episode. This is one of the "calibration events" used by McCracken et al. (2001a) to establish the relation between the impulsive NOy deposition in polar ice and the >30 MeV solar proton fluence.

The >30 MeV fluence values shown in Fig. 10 are similar to those derived by Feynman et al. (1993). The solar particle observations we utilized were acquired by the Johns Hopkins Applied Physics Laboratory Solar Proton Monitor on IMP 4 and 5 that are described in JHU/APL (1988). These data were originally published by Kohl et al. (1973). The basic spacecraft data was acquired from the NASA National Space Science Data Center (NSSDC). We have evaluated the data for the August 1972 events assuming that the total counting rate had a 30% contribution due to >0.7 MeV electrons (C.O. Bostrom, Private communication, 1974). We note that the maximum flux value at Earth occurred as the Earth was between two converging shocks. It has been previously noted that the peak flux values on 4 August observed by the Pioneer 9 spacecraft at 0.77 AU at an

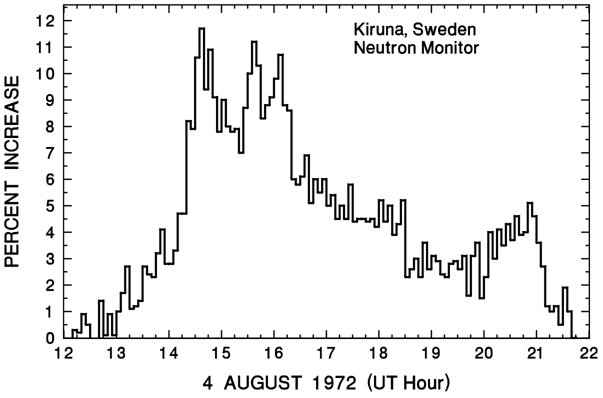

Fig. 8. The solar cosmic ray intensity recorded by the Kiruna, Sweden neutron monitor for the ground level enhancement (GLE) component of the 4 August 1972 solar–terrestrial event.

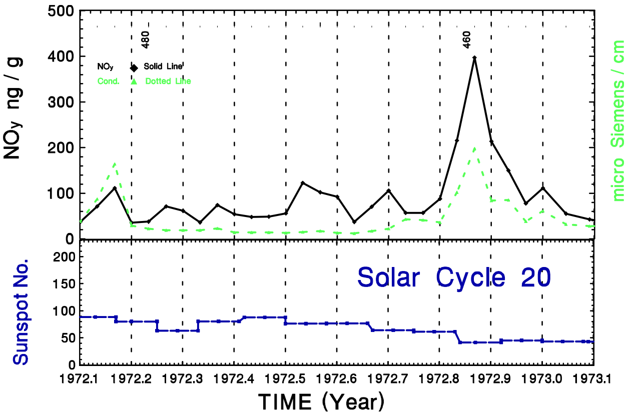

Fig. 9. The impulsive nitrate deposition event in Antarctica that corresponds to the August 1972 solar proton events. The dark line shows the nitrate concentration in units of nanograms per gram of water. The dotted line indicates the electrical conductivity in μS cm$^{-1}$. The sample number in the ice core is indicated at the top of the figure. The monthly sunspot number for this period of solar cycle 20 is indicated at the bottom of the figure.

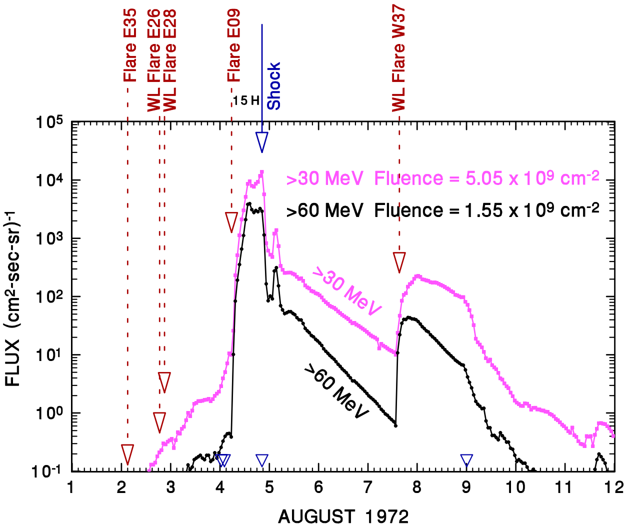

Fig. 10. Earth-orbiting spacecraft observations of the >30 and >60 MeV proton flux during the August 1972 solar–terrestrial event. The counting rates of the original data have been corrected assuming a 30% response from solar electrons. The times of associated solar flares (WL is an abbreviation for white light) are indicated at the top of this figure. The times of the interplanetary shock event at the Earth, are indicated by the geomagnetic sudden commencement (SC) events, denoted by triangles at the bottom of the figure.

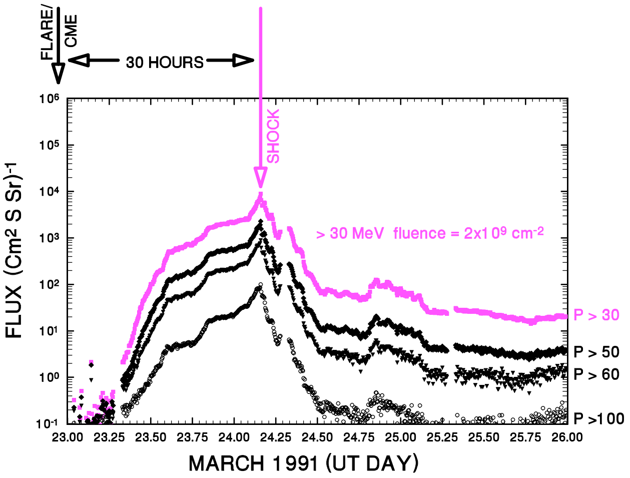

Fig. 11. GOES spacecraft observations of the solar proton flux during March 1991. The times of the associated solar flare and subsequent interplanetary shock arrival at 1 AU are illustrated at the top of the figure.

Earth–sun probe angle of 46°E was approximately an order of magnitude lower than that observed by Earth orbiting spacecraft (Smart et al., 1990).

### *4.4. The March 1991 event*

Fig. 11 presents the GOES spacecraft observations of the solar proton flux during March 1991. (The associated active region was at 28°E; see Fig. 1 for the relative position of this event compared with other “satellite era” large fluence solar proton events.) This large fluence event has the characteristic “soft” solar proton spectrum typical of events associated with activity near the solar central meridian and the maximum flux occurs as the interplanetary shock passes the Earth. In spite of the high >30 MeV peak flux values, there is not sufficient proton flux at 0.4 GeV to generate a response in sea level polar neutron monitors. A comparison of these flux values with the >30 and >60 MeV solar proton flux for August 1972 (shown in Fig. 10) indicates that the solar particle spectrum for August 1972 was slightly harder, in that there was sufficient flux at 0.4 GeV to generate a small (11.5%) response in the high latitude sea level neutron monitors.

## 5. Possible intensity–time solar proton flux profile for the Carrington event

### *5.1. Discussion of solar activity and possible multiple injections of solar protons*

The white light flare observed by Carrington was probably the dominant member of a sequence of a solar activity episode in August–September 1859. From an examination of the historical data, the first recorded magnetic disturbance occurred on 26 August when a magnetic declination change was recorded between “9.30 AM and noon” (Comptes Rendus, 1860). Extracts from this historic record indicate continuing activity for many days: “on 28 August the motion of all magnetic instruments was very irregular”; “during the forenoon on the 29th the declinometer was very much disturbed”; “a fresh disturbance commenced on the 1st of September at $11^{\mathrm{h}}$ $30^{\mathrm{m}}$”; “about 4 PM September 2d, there commenced a new magnetic storm more violent than that of August 29 … the magnets were carried beyond the range of their scales”.

We speculate that the Carrington solar flare was the most important event of an episode of solar activity that began before the Carrington solar flare event and may have continued after the observation of the Carrington white light solar flare. The geomagnetic and auroral observations strongly suggest solar activity both before and after the Carrington white light solar flare. The Carrington white light solar flare on 1 September 1859 is probably the dominant activity of this episode because of the associated very large reconstructed Dst event (Tsurutani et al., 2003) and low latitude auroral observations (Kimball, 1960). There were also observations of low latitude aurora on 28 August (Kimball, 1960) and we consider it likely that there may have been an initial flux of solar protons associated with this earlier solar activity. It therefore appears likely that there were multiple interplanetary shocks in the interplanetary space. In this respect, the Carrington activity episode may have been similar to the August 1972 episode of solar activity with the possibility of multiple converging interplanetary shocks. McCracken et al. (2001b) have previously estimated that the Carrington proton event in Fig. 4 had a fluence that was a factor of 2 to 3 times that implied by the “streaming limit” (Reames, 1999). They suggested that this could be due to either (a) a number of independent solar proton events within the resolution time of the nitrate data, or (b) that the converging shock scenario could provide a method for generating very large flux events that exceed the streaming limit. In the latter case, the multiple converging shocks would have contributed both to the peak flux that occurs as the dominant very fast interplanetary shock passes the Earth, and to the total fluence responsible for the large NOy impulsive event found in polar ice. Since the NOy events are time-integrated composites over many weeks, we cannot use these data to resolve events on a time scale of less than one month.

### *5.2. Possible solar proton flux profile based on multiple solar events with a dominant interplanetary shock source*

Based on the characteristics of the solar central meridian events just described, we have constructed a number of possible proton flux profiles consistent with the estimated fluence of the large enhancement in the nitrate data. We have modeled the principal Carrington event as a large shock associated event having a maximum flux at the presumed shock passage by the Earth. When we do this, the resultant maximum proton flux at energies >30 MeV can become ~$10^5$ ($\mathrm{cm}^2$ s ster$)^{-1}$. Colleagues have strongly suggested the particle flux associated with the Carrington event should be modeled as an episode of several particle events of approximately equal fluence. The evidence, as it stands, does not support such an alternative model. We are reluctant to hypothesize arbitrary events, and so we have restricted our hypothetical pre- and post-Carrington solar event to what we consider to be probable solar activity.

There is no doubt that there was prior solar activity, perhaps on 27 August (Shea et al., this issue), that resulted in the outstanding geomagnetic storms on 28 and 29 August (Royal Greenwich Observatory, 1955), and outstanding low latitude auroral events that are further documented in this issue (Green and Boardsen, this issue; Humble, this issue; Shea et al., this issue). This suggests there was an outstanding solar event on 27 August 1859 at ~50° east helio-longitude. This position results from assuming the solar event occurred in the Carrington active region that was at 12° West helio-longitude on 1 September 1859 (Chapman and Bartels, 1940). Assuming a normal solar rotation rate, this region would have been at ~50° East helio-longitude (Shea et al., this issue) 5 days earlier. Using the July 1959 solar activity episode as a model, we assume that this earlier solar activity generated a $10^9$ omni-directional solar proton fluence that peaked at Earth with the maximum of the geomagnetic storm at 21 UT on 28 August 1859. We have utilized the solar proton prediction system (PPS87, Smart and Shea, 1989) to generate a realistic exponential decay profile expected for solar proton events from solar activity at ~50° east helio-longitude. It is possible that there was other solar activity resulting in the disturbance on the “forenoon” of 29 August (Comptes Rendus, 1860). We have not hypothesized any other significant solar events from the afternoon of 29 August until the Carrington event on 1 September because of the lack of specific reported phenomena. The Royal Greenwich Observatory (1955) catalogue reports a “relatively undisturbed trace” during this time interval until the Carrington event.

The possible proton flux profile shown in Fig. 12, is strongly influenced by a composite of the >30 MeV flux profiles of the July 1959, August 1972 and the October 2003 events. We assume there was an initial significant solar proton event maximizing with the magnetic storm on 28 August 1859. We also assume that the Carrington white light solar flare on 1 September 1859 was the dominant solar proton event of this period and was associated with an initial soft spectrum GLE (see Section 5.3). For the construction of the solar proton event profile in Fig. 12, we assume that the Carrington white light solar flare at 12° West helio-longitude and associated fast interplanetary shock phenomena dominate the proton event flux profile at flux maximum. The assumption

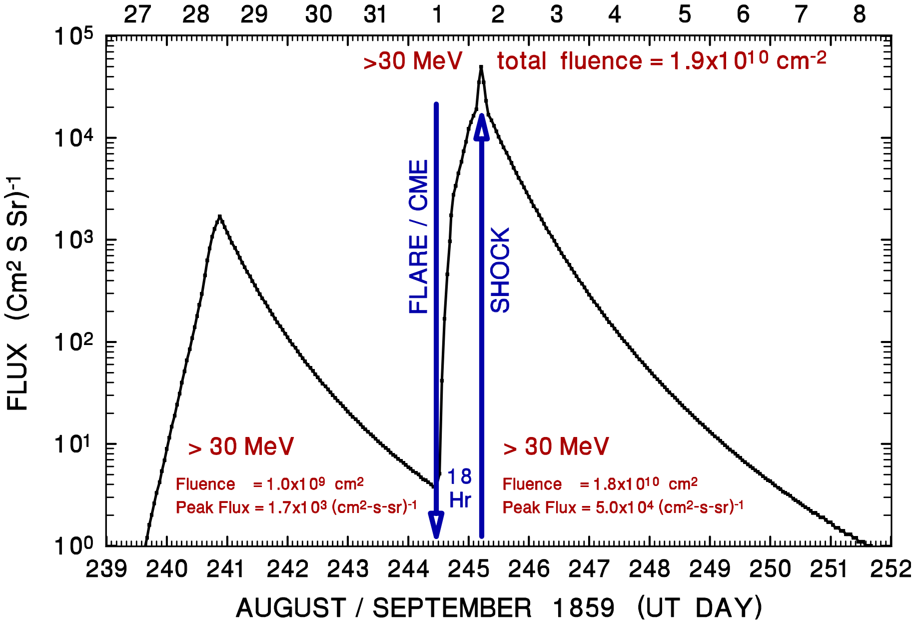

Fig. 12. Possible >30 MeV proton flux profile for the Carrington activity episode. It is assumed that there was a solar event on 27 August responsible for a pre-Carrington solar proton event that corresponds to aurora and geomagnetic activity on 28 and 29 August. The times of the Carrington solar flare and dominant interplanetary shock arrival at the Earth are illustrated by the arrows. The Carrington event flux profile assumes that the proton event began as a soft spectrum GLE. The maximum flux is assumed to occur at the beginning of the major magnetic disturbance, which we interpret as the interaction of the interplanetary shock with the Earth’s magnetosphere.

of an initial soft spectrum GLE requires a rapid increase at the beginning of the event from the pre-event background. This initial flux profile is modeled after the October 2003 event for its onset and initial rapid increase, and then the flux profile is assumed to be dominated by the fast interplanetary shock event, as was the case for 4 August 1972. We assume that the peak >30 MeV solar proton flux associated with the Carrington solar flare would have occurred as the very fast interplanetary shock passed the Earth 17.5 h after the visible solar flare. The flux–time integral of the composite solar proton flux profile is constrained to be $1.9 \times 10^{10}$ cm$^{-2}$, consistent with the fluence determined from the NOy event analysis.

While there are many possible choices of intensity–time profiles, the few hours around the maximum proton flux have the greatest contribution to the integral flux. Since there is a very fast interplanetary shock, we assume a rapid flux rise and fall around the interplanetary shock passage, similar to the August 1972 and the October 1989 events. In the profile displayed, we assume the "shock spike" is an increase of approximately a factor of two, similar to the October 1989 shock profile. After the "shock spike", we have assumed a typical exponential decay rate modeled after the prediction from the PPS87 model. This model quite satisfactorily reproduces the decay rate of the August 1972 events after the "shock spike" (Smart, 1988). Since the total integrated >30 MeV fluence for the Carrington event is ~4 times the August 1972 fluence, our model implies that the peak proton flux was ~4 times the >30 MeV peak proton flux observed during the 4 August 1972 event (see Fig. 12). Clearly, there must be a considerable degree of uncertainty regarding any reconstruction of the Carrington associated particle event. As discussed above, our model has been constrained as tightly as possible by our modern knowledge, and the historic evidence. Other scenarios could lead to higher, or lower estimates of the peak fluxes. Uncertainty must remain, and all reconstructions such as Fig. 12 must be used with care.

It is possible to insert smaller proton events (peak flux $\leqslant 1000$ cm$^{-2}$ s$^{-1}$ str$^{-1}$) at arbitrary positions in the intensity–time profile shown in Fig. 12 without causing a significant effect on the total fluence. It is also possible to construct higher >30 MeV peak proton fluxes, up to $\sim 10^5$ (cm$^2$ s str)$^{-1}$, but if these very high peak fluxes are used, then it is necessary to hypothesize a faster decay rate to remain within the total integrated fluence derived from the NOy deposition event associated with the Carrington event.

The historic records indicate that after the Carrington event, the next significant solar–terrestrial activity occurred on 13 October 1859 when there are reports of a significant, 24-h, magnetic storm and coincident mid-latitude aurora. The fact that this activity only resulted in mid-latitude aurora, compared to the low latitude aurora of the Carrington event, suggests that any associated proton events would have been smaller (peak flux $\leqslant 1000$ cm$^{-2}$ s$^{-1}$ str$^{-1}$), and would not make a significant contribution to the total fluence derived from the nitrate data.

### 5.3. Possible solar proton flux spectral parameters

The magnitude of the presumed associated GLE is speculative. There was no detectable GLE associated with the March 1991 event (omni-directional fluence of $1.8 \times 10^9$ cm$^{-2}$), which suggests that this event had a soft spectrum. The August 1972 event (peak flux >30 MeV of $\sim 2 \times 10^4$ (cm$^2$ s ster)$^{-1}$, omni-directional fluence of $5 \times 10^9$ cm$^{-2}$) generated an 11% GLE, and we use this as a nominal indicator of this class of event. Scaling the 1972 peak flux up an factor of 4, assuming the same type of relatively soft spectral parameters suggests a GLE of ~50% for the Carrington event. If we assume a single very high >30 MeV peak flux of $\sim 10^5$ (cm$^2$ s ster)$^{-1}$, then the possible GLE could be ~100%.

While we are not able to derive spectral information from the NOy data, we can place a limit on the Carrington event spectrum using the measurements of the cosmogenic isotope, $^{10}$Be, stored in the polar ice. McCracken et al. (2001c) have estimated that the hard spectrum GLE of 23 February 1956 would have increased the annual $^{10}$Be concentration by ~4%. This event is a member of the western member of the bimodal distribution in Fig. 3, and is known to have had a considerably harder spectrum than a GLE associated with central meridian solar activity. If the >30 MeV fluence of the Carrington event had these same hard spectral characteristics we calculate that there could have been an 80% increase in the annual concentration of $^{10}$Be. The annual $^{10}$Be data from Greenland for 1859 (Beer et al., 1990) show that any increase associated with the Carrington event was less than the 9% standard deviation of the annual data, clearly excluding a hard spectrum GLE.

We now test whether the Carrington event is consistent with the central meridian source of the bimodal distribution in Fig. 3. We have used the flux and spectral information for the August 1972 and March 1991 events as shown in Figs. 10 and 11 as indicative spectra, scaling up the flux values until we reached the fluence values for the Carrington event. We have then estimated the $^{10}$Be production from solar protons using the Webber and Higbie (2003) $^{10}$Be yield functions. These calculations did not result in a detectable amount of $^{10}$Be compared with the annual cosmic ray production; this being consistent with the actual $^{10}$Be data as discussed above. These calculations, together

Table 2
Important characteristics of our reference events and the Carrington event

| Event | >30 MeV peak flux $(\mathrm{cm}^2\ \mathrm{s\ ster})^{-1}$ | >30 MeV fluence $(\mathrm{cm}^{-2})$ | GLE |
|---|---|---|---|
| October 2003 | $4 \times 10^3$ | $3 \times 10^9$ | 14% |
| March 1991 | $9 \times 10^3$ | $2 \times 10^9$ | None |
| August 1972 | $2 \times 10^4$ | $5 \times 10^9$ | 11% |
| September 1859 | $1 \times 10^5$ | $1.9 \times 10^{10}$ | Probable, ~50% to ~100% |

Table 3
Deduced characteristics of the solar protons associated with the Carrington event

| Flare onset | 1 September, $11^{\mathrm{h}}\ 15^{\mathrm{m}}$ UT |
|---|---|
| Sudden commencement | 2 September, $04^{\mathrm{h}}\ 50^{\mathrm{m}}$ UT |
| Transit time | $17^{\mathrm{h}}\ 15^{\mathrm{m}}$ |
| Integrated >30 MeV fluence | $1.9 \times 10^{10}\ (\mathrm{cm}^{-2})$ |
| Possible peak >30 MeV flux | $\sim 5 \times 10^4$; probably $< 10^5\ (\mathrm{cm\ s\ str})^{-1}$ |
| Ground-level enhancement | Probable, ~50% to 100% (neutron monitor equivalent increase) |
| Spectra | *Soft*, similar to August 1972 |

with the $^{10}$Be measurements, establish that the solar protons associated with the Carrington event probably had a "soft" spectrum consistent with the other members of the central bimodal distribution, as listed in Table 1.

In Table 2, we detail some important characteristics of our reference events and the Carrington event. In Table 3, we summarize our deduced characteristics of the solar protons associated with the Carrington event.

## 6. Conclusions

We have constructed a possible >30 MeV solar proton intensity–time profile for the Carrington solar flare event of September 1859 that is consistent with a >30 MeV proton omni-directional fluence of $1.9 \times 10^{10}\ \mathrm{cm}^{-2}$ based on the analysis of solar proton generated NOy radicals that are deposited in polar ice. This intensity–time profile was based on the assumption that the maximum particle flux would be observed as the interplanetary shock passes the Earth. The cosmogenic $^{10}$Be data indicate that it was a soft spectrum event, consistent with the spectral characteristics of solar proton events observed in the space era that are associated with major central meridian solar activity.

## Acknowledgment

The research at the University of Maryland was supported by NSF Grant ATM 0107181.

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