The frequency distribution of solar proton events: 5 solar cycles and 45 solar cycles

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Abstract

Very large solar proton events, those having an omni-directional solar proton fluence greater than 10^9 cm^{-2} at energies >30 MeV, impose operational constraints on manned space missions and equipment. Solar particle data from earth-orbiting spacecraft for the last 5 solar cycles are often used to generate a proton event frequency distribution. The analysis of impulsive NOy events in polar ice results in an ~450-year record of very large solar proton events. The frequency distribution of these large events is consistent with the frequency distribution derived from the analysis of radionuclides found in moon rocks. This long-term record indicates that solar proton events with a >30 MeV omni-directional fluence exceeding 6 x 10^9 cm^{-2} are very rare. However, the number of very large fluence solar proton events per solar cycle is extremely variable, ranging from 0 to 8 per solar cycle.

1. Introduction

Very large solar proton events, those having an omni-directional solar proton fluence >1 x 10^9 cm^{-2} at energies >30 MeV impose operational constraints on manned space missions and equipment such as the requirement for storm shelters with sufficient shielding to reduce the radiation dose to tolerable levels or the need to protect or actually turn off sensitive equipment that may be susceptible to soft errors or radiation damage. Figure 1 illustrates the >30 MeV solar proton events observed since the beginning of the 19th solar cycle. In the >30 MeV energy range, the most commonly occurring events are those with an omni-directional fluence in the 10^5 to 10^6 cm^{-2} range. The very large events are those 3 orders of magnitude larger - those with fluence >1 x 10^9 cm^{-2}. These very large events only occur a few times in a solar cycles, or in the case of solar cycle 21 may not occur in a solar cycle. In this figure we have indicated the 10^9 cm^{-2} omni-directional solar proton fluence level by a dashed line.

1. The frequency distribution of solar proton events

As a result of solar particle event monitoring by NASA and NOAA, the most commonly reported solar proton events during the “space era” are those with energies >10 MeV. When we examine the frequency distribution of the >10 MeV solar proton events observed at the Earth, we find two distinct groups.

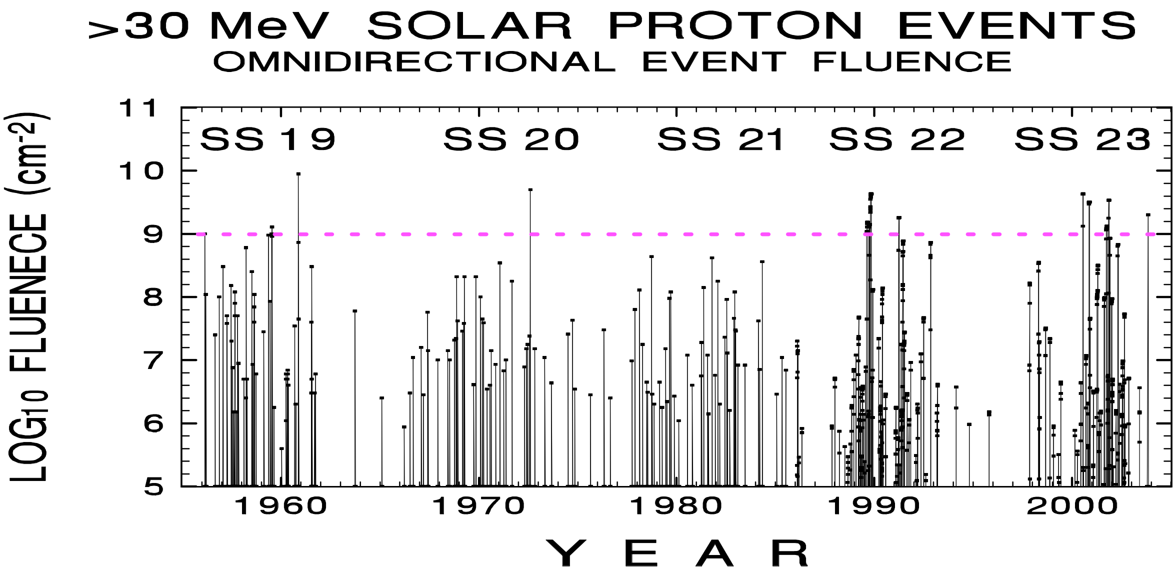

Fig. 1. The >30 MeV solar proton events since solar cycle 19.

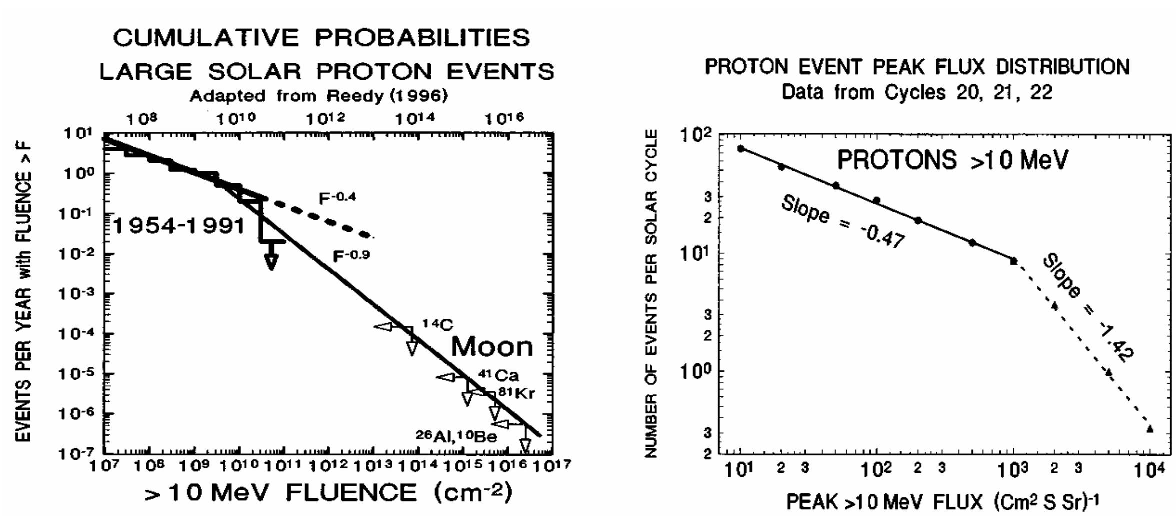

Fig. 2. Left: The fluence distribution of solar proton events. The solid (stepped) line indicates fluences actually observed. The dashed line is an extension of the slope of the most frequently occurring events. The solid line extending to the right with the “Moon” label indicates the extreme upper limits of the solar proton fluences estimated from the analysis of induced radioactivity in moon rocks. Right: The peak flux distribution of earth-sensed solar proton events. The solid line indicates the distribution of the most frequently occurring events. The dashed line indicates the large peak flux events.

The resulting broken power law distribution was first published by Lingenfelter and Hudson (1980). The first group consists of the common and most frequently observed events and has been reproduced by many investigators (van Hollebeke et al., 1975; Cliver et al., 1991; Gerontidou et al., 2002; Kurt, et al., 2004). The second group is the distribution of the very large fluence events. These are rare events often excluded from frequency analyses since they “do not fit and must be anomalous”. However, a careful analysis of the entire solar proton database consistently reproduces the broken power law distribution shown in Figure 2.

Figure 2 illustrates the >10 MeV proton fluence and flux distribution. The left panel (from Reedy, 1996) illustrates the >10 MeV proton fluence distribution. The most frequently observed events are illustrated by the line at the top left. The upper limit of the rare very large fluence events is illustrated by the line on the right side of this panel. Note that a broken power law is a reasonable approximation to this fluence distribution. The distribution of the most commonly occurring events, when extrapolated to the large fluences, does not match the frequency distribution of the very large fluence events. In fact, the slope extrapolation of the most commonly occurring events exceeds the upper limits derived from the radioactivity induced in moon rocks by proton bombardment. The right panel of this figure illustrates an independently derived (Smart and Shea, 1997) for the peak flux distribution. Note that this peak flux distribution is also best-represented by a similar broken power law.

3. The long-term record of proton events in polar ice

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. Measurements of impulsive nitrate deposition in polar ice are markers of the HNO_3 precipitation. Contemporary state-of-the-art measurements of the denitrification of the polar atmosphere (Spang et al., 2005) find significant nitric acid trihydrate particles (called NAT rocks) in the polar stratospheric clouds. Some of the produced HNO_3 is transported to the troposphere, where it is precipitated downward to the surface.

This nitrate radical generation and consequent ozone depletion has been observed for every major large fluence solar proton event of the space era (see Jackman et al., 2000; Jackman et al., 2001 and included references). There is a large background of terrestrial sources of NOy (see Jackman et al., 1980, 2000), and only very large fluence solar proton events (those with a >30 MeV omni-directional fluence of approximately 1 x 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 occurs ~6 weeks after the initiating solar proton event (Zeller and Dreschhoff, 1995; Dreschhoff and Zeller, 1990, 1998). Figure 3 displays an example of these impulsive nitrate events in the interval from 1890-1898.

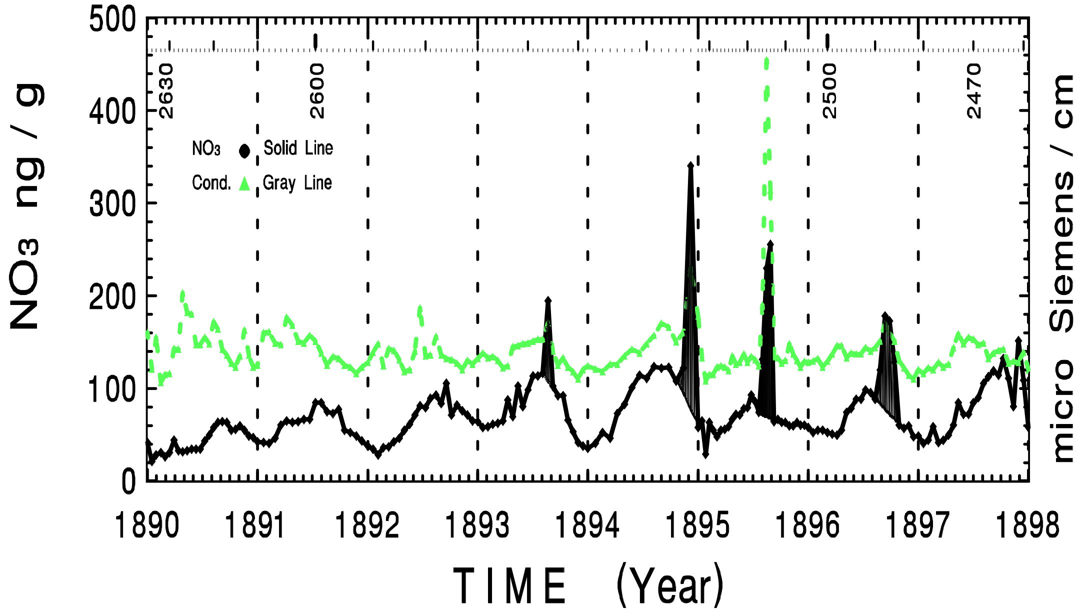

Fig. 3. The impulsive nitrate events in the interval from 1890-1898. The black line shows the nitrate concentration in units of nanograms per gram of water. The light line indicates the electrical conductivity in μS cm^{-1}. The sample number in the ice core is indicated at the top of the figure.

In 1992 an ice core 125.6 meters in length (named GISP2-H) was obtained at Summit, Greenland (72° N, 38° W), specifically for ultra-high resolution nitrate studies. Dating of this core established that the precipitation was deposited in the years between 1561 and 1992. Using the calibration between impulsive nitrate concentration and solar proton events derived by McCracken et al. (2001a), the analysis of the core resulted in the identification of 154 impulsive nitrate enhancements with a >30 MeV omni-directional fluence >0.8 x 10^9 cm^{-2} (the probable 3-sigma detection threshold) for the period 1561-1950. The resulting ~450-year history of large fluence solar proton events is shown in figure 4.

The independent analysis of two additional shallow 30 meter cores obtained from Summit, Greenland in the summer of 2004 have verified the existence of the impulsive nitrate deposition associated with known solar particle events during the last 60 years.

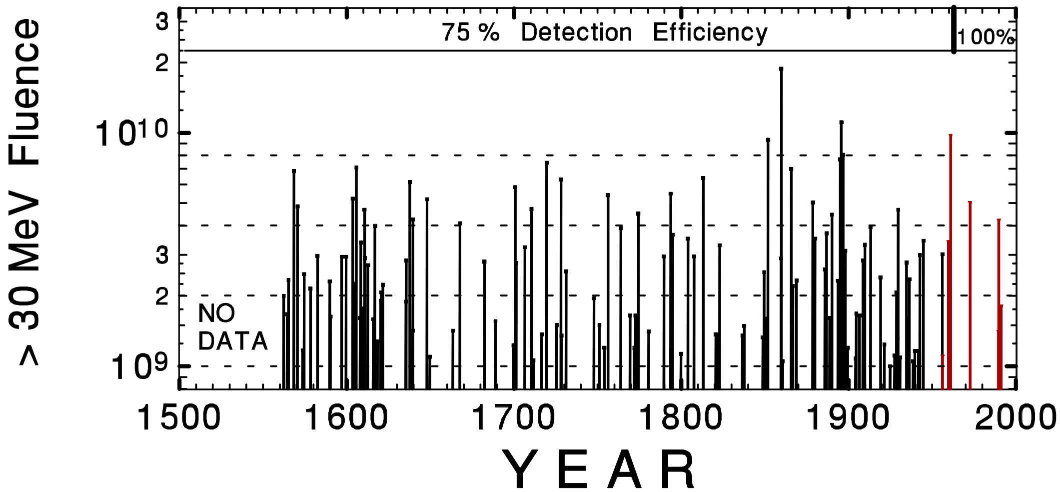

Fig. 4. The ~450-year record of >30 MeV solar proton fluence events. The black lines are from the NOy analysis Proton events (1965-2000) are indicated by the red lines. (From McCracken et al., 2001b)

The frequency distribution of this ~450-year record of solar proton events identified from the analysis of impulsive nitrate deposition (NOy) events found in polar ice is consistent with those from the last five solar cycles. Both of these frequency distributions are presented in figure 5. In this figure the black line indicates earth-sensed modern era solar proton events (the same data as used in the right side of figure 4. The diamonds indicate large proton events derived from the analysis of "impulsive" nitrate events in ice cores. The dashed line is an extrapolation of the slope of the most commonly observed proton events. The line extending to the right of the figure labeled "Moon" indicates the maximum possible proton flux limits determined from the analysis of radionuclides in moon rocks. We note that the frequency distribution of the very large events found by NOy deposition in polar ice is consistent with the frequency distribution derived from the analysis of radionuclide found in moon rocks. From this frequency distribution we note that solar proton events with a >30 MeV omni-directional fluence exceeding 6 x 10^9 cm^{-2} are very rare.

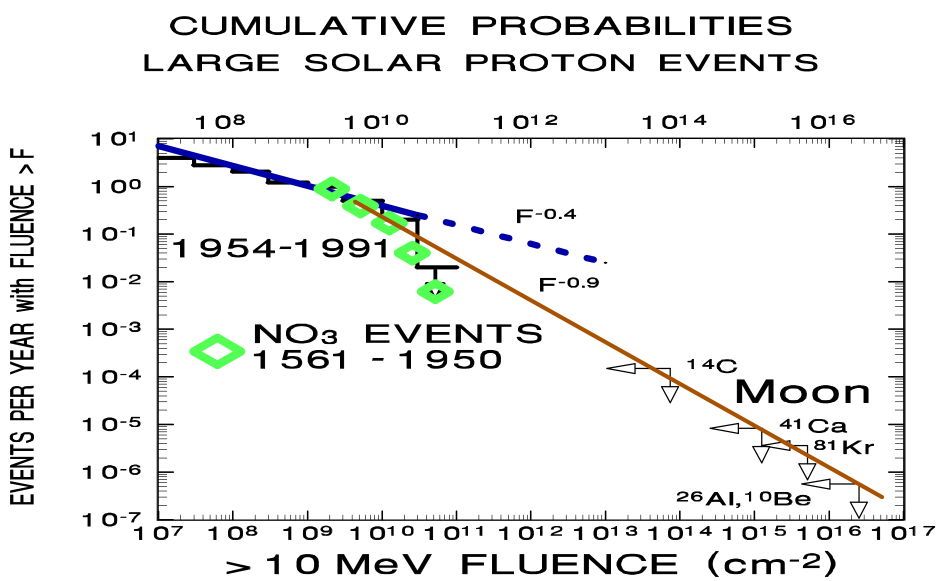

Fig. 5. The ~450-year frequency distribution of solar proton events. The black line indicates earth-sensed modern era solar proton events. The diamonds indicate proton events from the analysis of NOy events in ice cores. The dashed line is an extrapolation of the most commonly observed proton events. The solid line labeled "moon" indicates the limits determined from the analysis of radionuclides in moon rocks.

4. The most extreme solar proton events.

The most extreme >30 MeV omni-directional solar proton fluence events for the last 5 solar cycles are 8 x 10^9 cm^{-2} for the November 1960 solar activity episode and 5 x 10^9 cm^{-2} for the August 1972 solar activity episode (Shea and Smart, 1990; Feynman et al, 1993). An examination of figure 1 shows the relative magnitude of these large events with respect to the most frequently occurring events. An inspection of figure 4 shows the relative magnitude of these “space era” events with the ~450-year record derived for impulsive nitrate events in polar ice. The largest fluence event displayed in figure 4 corresponds to the Carrington event of 1859 (Carrington, 1860) with an omni-directional solar proton fluence of 2 x 10^{10} cm^{-2}. This largest fluence event is ~4 times the fluence of the August 1972 episode or 2 ½ times the fluence of the November 1960 episode. (See Smart et al., 2006 for a detailed analysis of the Carrington event.) This again suggests that solar proton events with a >30 MeV omni-directional fluence exceeding 6 x 10^9 cm^{-2} are very rare.

However, as noted by McCracken et al. (2001b) the number of large fluence solar proton events per solar cycle is extremely variable. During the well known periods of prolonged solar minimum, there may be no large solar proton events in a solar cycle. There may also be no very large solar proton events during a reasonably active solar cycle, such as happened during solar cycle 21. The ~450 year record shows that the number of very large fluence solar proton events per solar cycle may range from 0 to 8 per solar cycle.

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