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SOLAR PROTON FLUENCE FOR 31 SOLAR CYCLES DERIVED FROM NITRATE ENHANCEMENTS IN POLAR ICE

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Abstract: Using nitrate enhancements in the polar ice as a proxy for solar proton events, we have determined the proton fluence above 30 MeV for 31 solar cycles between 1610 and 1954 (cycle -12 through cycle 18). Our results show a wide range of solar proton fluences over these 31 solar cycles, from three cycles with no significant proton events above 109 cm-2 to a high of 38 x 109 cm-2. In a comparison of the two cycles with the highest solar proton fluence, we find that cycle 10 was dominated by one major event (the Carrington event in 1859) while cycle 13 had 7 major events contributing to the total fluence. The total fluence for most cycles is within a factor of 2 of the maximum fluence per cycle measured by spacecraft since 1965. Until new deep ice cores are available for both calibration with known fluences and for verification of the original results, these derived solar proton fluences over a number of solar cycles represent the only available values as upper limits for space exploration experiments.

Introduction

Predictive models of the probable proton fluence to be experienced by a future space mission are of considerable interest to space mission planners. At the present time there are two principal models: the JPL model [1-3], and the Xapsos model [4,5]. Each of these models uses different methodologies to develop the probable proton fluences, but they essentially all use the same data base. These are the early Earth-sensed polar ionospheric measurements converted to proton flux for the 19th solar cycle and direct satellite measurements since the 20th solar cycle. Some models include the 19th solar cycle data and others prefer to use only the direct satellite sensed proton data. Figure 1 illustrates the available >30 MeV solar proton data from cycle 19 to the present.

The JPL model [1-3] employs a log-normal distribution to fit the significant solar proton events. However, in employing a log-normal distribution, the user must make some assumptions about an upper cutoff value (worst case), otherwise there is a finite probability of getting an event, no matter how large. Figure 2 displays the JPL model fit to the >30 MeV proton fluence data.

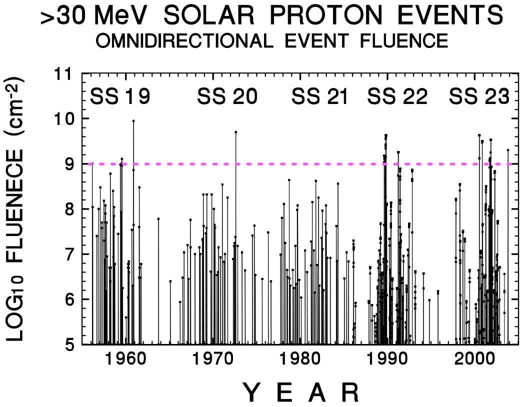

Figure 1: The >30 MeV solar proton events since solar sunspot cycle 19.

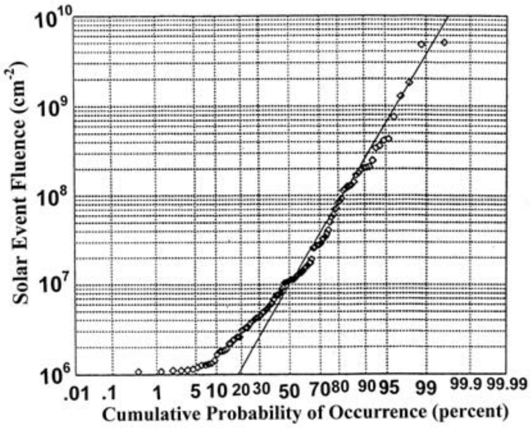

Figure 2: The JPL model [2] distribution of the >30 MeV solar event fluences for active years.

The Xapsos model [4,5] employs the maximum entropy principal. The distribution results in a truncation of the peak and has a smooth transition to zero at some maximum value. Figure 3 displays the Xapsos model fit to the >30 MeV proton fluence data.

Both of these models could be improved if there were some method to define the maximum credible solar proton event fluence. We believe the impulsive nitrate deposition record in the polar ice can provide a realistic upper limit of the maximum credible solar proton event.

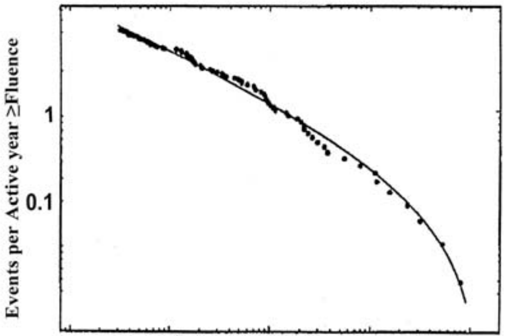

Figure 3: The Xapsos model [5] distribution of the >30 MeV solar proton fluence data during the active years of solar cycles 20-22.

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 NO_y) 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 [6] 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 [7,8] and included references). There is a large background of terrestrial sources of NO_y and only very large fluence solar proton events (those with a >30 MeV omni-directional fluence of approximately 0.8×10^9 cm^{-2}) will generate sufficient NO_y to be observable above this terrestrial background. The experimental evidence from high-resolution sampling of polar ice cores indicates that the deposition of these NO_y radicals in polar ice occurs ~4-6 weeks after the initiating solar proton event. 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. [9,10], the analysis of the core resulted in the identification of 154 impulsive nitrate enhancements with a >30 MeV omni-directional fluence $>0.8 \times 10^9$ 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 frequency distribution of this ~450-year record of solar proton events identified from the analysis of impulsive nitrate depositions (NO_y events) found in polar ice is relatively consistent with those of the last five solar cycles.

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 large solar proton events during the last 60 years [11].

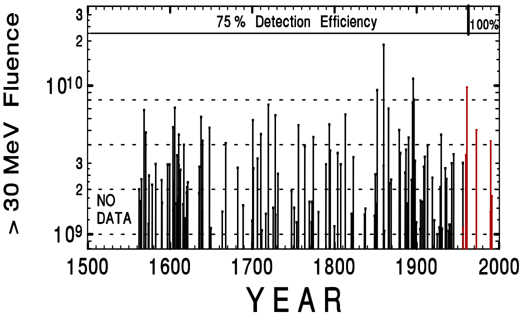

Figure 4: The ~450-year record of >30 MeV solar proton fluence events. The black lines are from the NO_y analysis. Proton events (1965-2000) are indicated by the red lines. (From McCracken et al., [10]).

Discussion

The >30 MeV solar proton fluence data for 36 solar cycles is presented in Table 1. In our opinion these are the best currently available data for the long-term behavior of the solar proton environment of the Earth. These data, summed over each solar cycle and plotted in figure 5, show the extremes in solar proton fluence. The 13th solar cycle had 7 very large solar proton fluence events and has the largest solar cycle accumulated fluence in the ~450-year record. The second highest fluence (solar cycle 10) is primarily from a single activity episode, the Carrington Event in 1859. (See [12] for an analysis of this event.) We note that the largest solar cycle accumulated fluences prior to the space era are within a factor of ~2 of the maximum of our space era spacecraft measured record of solar proton event fluence accumulated over a solar cycle.

From previous studies [12,13] we further note that the largest single event fluence is only ~4 times the fluence of the August 1972 solar activity episode in solar cycle 20 or about ~2 times the fluence of the November 1960 solar activity episode of the 19th solar cycle.

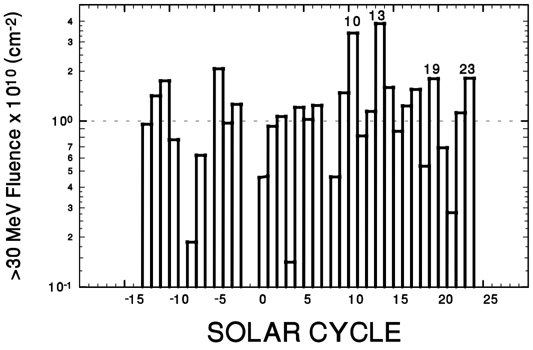

Figure 5: The > 30 MeV omnidirectional proton fluence for 36 solar cycles.

Table 1: > 30 MeV Fluence per sunspot cycle

Cycle #	Fluence 10^{10} cm^{-2}	Start	End
-12	0.96	1610.8	1619.0
-11	1.42	1619.0	1634.0
-10	1.75	1634.0	1645.0
-9	0.78	1645.0	1655.0
-8	0.10	1655.0	1666.0
-7	0.19	1666.0	1679.5
-6	0.62	1679.5	1689.5
-5	0.00	1689.5	1698.0
-4	2.06	1698.0	1712.0
-3	0.97	1712.0	1723.5
-2	1.26	1723.5	1734.0
-1	0.00	1734.0	1745.0
0	0.47	1745.0	1755.2
1	0.93	1755.2	1766.5
2	1.07	1766.5	1775.5
3	0.14	1775.5	1784.7
4	1.21	1784.7	1798.3
5	1.03	1798.3	1810.6
6	1.24	1810.6	1823.3
7	0.00	1823.3	1833.9
8	0.46	1833.9	1843.5
9	1.48	1843.5	1856.0
10	3.39	1856.0	1867.2
11	0.81	1867.2	1878.9
12	1.14	1878.9	1889.6
13	3.87	1889.6	1901.7
14	1.59	1901.7	1913.6
15	0.87	1913.6	1923
16	1.24	1923.6	1933.8
17	1.55	1933.8	1944.2
18	0.53	1944.2	1954.3
19	1.80	1954.3	1964.9
20	0.69	1964.9	1976.5
21	0.28	1976.5	1986.8
22	1.12	1986.8	1996.8
23	1.81	1996.8	2007

The impulsive nitrate deposition record in the polar ice provides a realistic upper limit of the maximum credible solar proton event. This limit could be included in the JPL model and would not significantly change the probable solar proton fluence that this model predicts for a future space mission. The inclusion of NO_y events (or the NO_y upper limit) would probably have more of an effect on the Xapsos model in that it would probably increase the maximum cutoff. (The inclusion of the 23rd solar cycle data would have a similar effect since it has been a very active cycle).

Conclusion

The cumulative >30 MeV proton fluence for each of the 36 solar cycles between 1610 and 2007 (cycle -12 through cycle 18 determined from NO_y analysis; cycle 19 to present derived from space era data) shows a wide range of solar proton fluences. The total solar cycle fluence for most cycles is within a factor of ~2 of the cumulative solar cycle maximum fluence measured by spacecraft since 1965. The maximum single event fluence (Carrington event, 1859) is a only a factor of ~2 greater than the maximum event (November 1960) of the last 5 solar cycles.

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