UPDATE ON SOLAR-PROTON FLUXES DURING THE LAST FIVE SOLAR ACTIVITY CYCLES.

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Summary: The event-integrated fluences of energetic solar protons during the last 5 solar cycles (1954-2008) have been re-evaluated. This database is important in providing good predictions for space missions, such as Dawn now in orbit around the asteroid 4 Vesta.

Introduction: This time period (1954-2008) consists of solar-activity cycles 19 to 23. The average length of a solar cycle (SC) is about 11 years. The results reported here are almost-final results of a re-evaluation. Previous sets of event-integrated solar proton fluences have been reported for 1956 to 1973 (solar cycles 19 and 20) [1], 1972 to 1986 (mainly solar cycle 21) [2], and 1997 to 2005 (almost all of solar cycle 23 [3]). Only preliminary average solar proton fluxes for the period 1986-1996 (solar cycle 22) were reported [4]. Solar proton fluences for 1954-1964, which are based on indirect measurements [1] and ^{22}Na profiles in lunar rocks, were revised using new data for cross sections [5]. Some solar particle events were not in these previous works, such as a large solar particle event (SPE) in Dec. 2006. New compilations of proton fluences for SPEs over long time periods have become available [e.g., 6] and several on-line databases now exist.

The fluxes of solar energetic particles (SEPs) are used for many studies, such as the study of the Sun [7] and the recent exposure histories of lunar samples [8]. The average fluxes over the last ~0.5 Myr are similar to those for the last 5 solar cycles but higher than average fluxes over the last ~1 Myr [8].

High solar-proton fluxes are a very serious radiation hazard in the inner solar system and have had serious effects on interplanetary spacecraft and on material exposed to these energetic protons. High flux events are disruptive to instruments that measure secondary radiation produced by galactic cosmic rays, such as the Gamma Ray and Neutron Detector (GRaND) on the Dawn mission [9].

The results of earlier work have shown that extremely large solar particle events, orders of magnitude larger than those observed recently, are very unlikely [7], a result consistent with work using solar-particle-produced nitrates in polar ice [10]. While extreme SPEs are unlikely, the largest observed SPEs are still very serious radiation hazards in space to humans, instruments, and spacecraft. Earlier work has shown that large SPEs are unlikely during the 2 years on either side of solar minimum [11]. The re-evaluation of SPEs reported here does not change earlier conclusions but give more-refined results.

Event-Integrated Solar-Proton Fluxes: A careful search of the literature was made to get all possible compilations of event-integrated solar proton fluences, plus a few of peak SPE fluxes as an additional check. The results for each possible SPE were compiled for the last 5 full solar cycles and examined. Results were only used if at least 2 independent sources listed it and if the event-integrated fluence above 30 MeV was 2×10^6 cm^{-2} or more. (For SC19, the limit >30 MeV was lowered to 1×10^6, as the original fluences were known to be low by a factor of about 2 [1,5].) The energy of 30 MeV was selected because recent works [8,10] have shown it to be more relevant than the previously used 10 MeV.

Among the data sources for more than 1 solar cycle not previous used were for 1956-1985 [11], for 1974-2002 from IMP-8 [6], 1974-2002 (but only >10 MeV) [12], and the on-line solar-proton values for 1974 to now for GOES and for 1967-2006 at the GSFC's OMNIWeb. These data allowed the comparison of results for more than 1 solar cycle.

Solar-cycle boundaries were selected to be the months with the lowest monthly smoothed sunspot numbers. For each SPE, the event-integrated fluences above 10-, 30-, 60-, and 100-MeV were averaged. For SC19, the results for >10, >30, and >100 MeV were used to calculate fluences >60 MeV, which is the highest energy with complete results for the 4 later solar cycles. For about half of the SPEs in SC19 (mainly in the first years), there were only results for >30 MeV. For the last 4 solar cycles used, the number of events for the final evaluated data set were about half of those in the database.

Average fluxes for each solar cycle. Table 1 gives the sums of event-integrated fluences at 1 AU from the Sun for these 5 solar cycles and their sum divided by the time for that period. Results for >100 MeV were omitted because the data set is incomplete. For the whole of SC19, the fluences >10 and >60 MeV were calculated using the >30 MeV results and an exponential rigidity spectra shape of 100 MV [5]. The values of the exponential rigidity parameter (R_0) are similar to those over the last 10^4 to 5×10^6 years [8]. For all other cycles, the fluences and rigidity were determined from satellite measurements. The fluences for the last 4 solar cycles are not better than about 20%.

Table 1. Sum of solar-cycle averaged solar-proton fluxes >10, >30, and >60 MeV and the exponential-rigidity spectral shape (R_0, in MV) for the last 5 solar cycles. Dates are months and year. The number of events used for each cycle is given (#). Average fluxes are in units of proton/cm^2/s using the actual length of each solar cycle (to the nearest month).

SC	Dates	#	>10	>30	>60	R_0
19	5/54-9/64	63	≈196	71	≈26	100
20	10/64-4/76	45	89	24	8	83
21	5/76-2/86	56	59	10	3	75
22	3/86-7/96	31	97	18	5	72
23	8/96-11/08	44	216	46	11	69
All	5/54-11/08	239	134	35	11	80

Cumulative frequency plots: Fig. 1 shows the cumulative number of SPEs as a function of the event-integrated fluences for 5/54 - 11/08. The SPE with the highest fluences was 4 August 1972, with fluences (F) >10, >30, and >60 MeV of 1.9×10^{10}, 7.0×10^9, and 2.35×10^9 protons/cm^2, respectively. The low numbers for the smallest fluences for >10 MeV are probably because some soft (low R_0) SPEs were not included using the adopted cutoff for >30 MeV.

The curves at lower energies are almost power laws. The exponents x for F^{-x}, are about 0.4, 0.45, and 0.6 for >10, >30, and >60 MeV, valid up to about 8×10^9, 2×10^9, and 7×10^8 protons/cm^2, respectively.

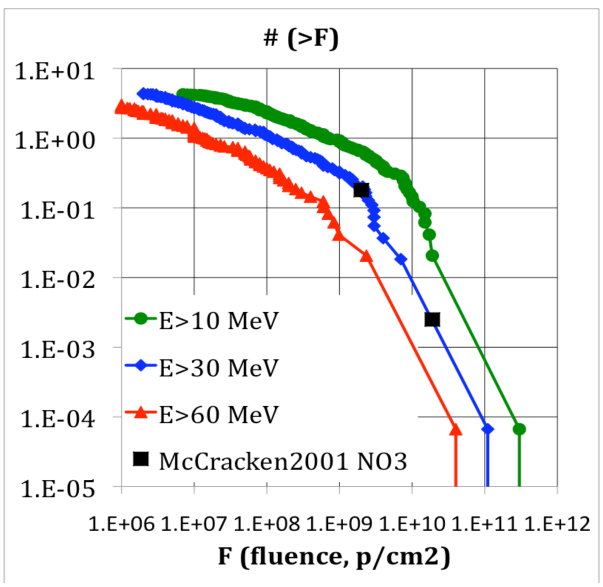

Fig. 1. Cumulative plot of the number of events per year for the last 5 solar cycles as a function of the fluence. For high fluences, the 2 black points for only >30 MeV are from SPE-produced NO_3 in ice cores from 1561-1950 [10]. The 3 upper limits shown for the highest fluences are based on ^{14}C tree-ring data over the last 7000 years [13].

The trend in Fig. 1 is consistent with the report of 70 SPEs with >30 MeV fluences of >2×10^9 from 1561 to 1950, which is one every 5.5 years [10].

For the highest fluences, there were only a few events, and the trend steepens considerably with increasingly higher fluences. This drop is consistent with other work. From ionization-produced nitrates in polar ice cores, the largest SPE since 1561 is estimated to have been on 1 Sept. 1859, the huge Carrington super white-light solar flare [10].

Upper limits for high-fluence SPEs were estimated from the lack of large spikes in tree-ring ^{14}C concentrations over the last 7000 years [13]. That highest fluence is plotted as a limit assuming 0.5 events per 7000 years. These ^{14}C points are very consistent with the drop for the highest fluences. The over-all trend in Fig. 1 is very consistent with earlier results for SPEs [7,10].

Summary: The results from this re-evaluation of event-integrated fluences of solar protons are better and more complete than earlier results, but the basic trends are similar. They show that the 4 August 1972 SPE is a reasonable choice as the largest probable SPE, which was a very serious radiation hazard, and would be disruptive and possibly damaging to instruments that measure space radiation (such as GRaND on Dawn). The probability of such a SPE occurring in a decade is ~20%. Slightly larger SPEs can occur but are very rare. SPEs more than an order of magnitude larger are very unlikely [cf., 10,13]. The fluences of SPEs in the asteroid belt and the Dawn spacecraft are probably ~0.2 of those at 1 AU [14].

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