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 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 reevaluation. 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 ¹⁸⁷⁷Na 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 fluxes, 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 $2 \times 10^6$ cm$^{-2}$ or more. (For SC19, the limit >30 MeV was lowered to $1 \times 10^6$, 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 $5 \times 10^5$ 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%.
the last 7000 years [13]. The highest fluences are based on
from 1561
fluence. For high fluences, the 2 black points for only
year for the last 5 solar cycles as a function of the
Fig. 1.
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8
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laws. The exp
because some soft (low R
for the smallest fluences for >10 MeV are probably
integrated fluences for 5/54
Cumulative frequency plots: Fig. 1 shows the cumu-
low and more complete than earlier results, but the b
rare. SPEs more than an order of magnitude larger are very
unlikely [cf., 10,13]. The fluences of SPEs in the apo-
slow but are
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 apo-
slow, and would
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Table 1. Sum of solar-cycle averaged solar-proton
fluences >10, >30, and >60 MeV and the exponen-
tial-rigidity spectral shape (R₀, 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/cm²/s using the actual length of
each solar cycle (to the nearest month).

<table>
<thead>
<tr>
<th>SC</th>
<th>Dates</th>
<th>#</th>
<th>&gt;10</th>
<th>&gt;30</th>
<th>&gt;60</th>
<th>R₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>5/54-9/64</td>
<td>63</td>
<td>196</td>
<td>71</td>
<td>26</td>
<td>100</td>
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<tr>
<td>20</td>
<td>10/64-4/76</td>
<td>45</td>
<td>89</td>
<td>24</td>
<td>8</td>
<td>83</td>
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<tr>
<td>21</td>
<td>5/76-2/86</td>
<td>56</td>
<td>59</td>
<td>10</td>
<td>3</td>
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<td>31</td>
<td>97</td>
<td>18</td>
<td>5</td>
<td>72</td>
</tr>
<tr>
<td>23</td>
<td>8/96-11/08</td>
<td>44</td>
<td>216</td>
<td>46</td>
<td>11</td>
<td>69</td>
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<tr>
<td>All</td>
<td>5/54-11/08</td>
<td>239</td>
<td>134</td>
<td>35</td>
<td>11</td>
<td>80</td>
</tr>
</tbody>
</table>

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 × 10¹⁰, 7.0 × 10⁹, and
2.35 × 10¹⁰ protons/cm², respectively. The low numbers
for the smallest fluences for >10 MeV are probably
because some soft (low R₀) 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 × 10⁹, 2 × 10⁹, and 7 × 10⁸ protons/cm², respectively.

The trend in Fig. 1 is consistent with the report of
70 SPEs with >30 MeV fluences of >2 × 10²⁸ 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 in-
creasingly higher fluences. This drop is consistent with
other work. From ionization-produced nitrates in pol-
ars, the largest SPE since 1561 is estimated to have been on 1 Sept. 1859, the huge Carrington super
light solar flare [10].

Upper limits for high-fluence SPEs were estimated
from the lack of large spikes in tree-ring 1⁴C concen-
trations over the last 7000 years [13]. That highest flu-
ence is plotted as a limit assuming 0.5 events per 7000
years. These 1⁴C 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].

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 NO₃ in ice cores
from 1561-1950 [10]. The 3 upper limits shown for the
highest fluences are based on ¹⁴C tree-ring data over
the last 7000 years [13].