Probability Estimates of Solar Proton Doses During Periods of Low Sunspot Number for Short Duration Missions

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In an earlier paper presented at ICES in 2015, we investigated solar particle event (SPE) radiation exposures (absorbed dose) to small, thinly-shielded spacecraft during a period when the monthly smoothed sunspot number (SSN) was less than 30. Although such months are generally considered "solar-quiet", SPEs observed during these months even include Ground Level Events, the most energetic type of SPE. In this paper, we add to previous study those SPEs that occurred in 1973-2015 when the SSN was greater than 30 but less than 50. Based on the observable energy range of the solar protons, we classify the event as GLEs, sub-GLEs, and sub-sub-GLEs, all of which are potential contributors to the radiation hazard. We use the spectra of these events to construct a probabilistic model of the absorbed dose due to solar protons when SSN < 50 at various confidence levels for various depths of shielding and for various mission durations. We provide plots and tables of solar proton-induced absorbed dose as functions of confidence level, shielding thickness, and mission-duration that will be useful to system designers.

Nomenclature

Al	=	chemical symbol for aluminum
cGy	=	absorbed dose unit centiGray
CL	=	confidence level
CME	=	coronal mass ejection
ESP	=	energetic storm particle event
GCR	=	galactic cosmic radiation
GeV	=	unit of energy Giga-electron volt
GLE	=	ground level event (or enhancement)
HZETRN	=	NASA Langley Research Center-developed high energy particle transport/dose code
MeV	=	unit of energy Mega-electron volt
rms	=	root mean square
SEE	=	single-event effect
SEP	=	solar energetic particle
SPE	=	solar particle event
SSN	=	smoothed sunspot number
TID	=	total ionizing dose

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Introduction

HISTORICAL NASA missions have been with large spacecraft undergoing long durations. However, under recent budget restrictions, there has been a paradigm shift in the types of missions NASA has undertaken to those with smaller vehicles and shorter durations. Since many of these missions are also under constrained budgets, new, low-cost, and efficient methods are being employed on these missions to make them successful. One area to consider for cost-efficiency is the design of the vehicle for radiation protection.

Furthermore, the recent trends in solar activity show a decrease in this activity from what has historically been normal in the manned spaceflight timeframe. The typical method of radiation analysis has been to consider the worst-case scenario for the radiation environment and then to design the vehicle to withstand the dose from that worst-case scenario. Thus, with the low-cost, short duration missions that are becoming more standard at NASA, using a historically worst-case method of analysis for total ionizing dose may lead to an overdesigned vehicle that is more costly than necessary.

In a previous paper[1], we began the process of developing a new method for radiation analysis by investigating the solar-proton environment during months in the historical record when the monthly smoothed sunspot number (hereafter "SSN") was less than 30. In that study, we found that the worst-case solar particle event might not be the worst-case scenario for relatively thin spacecraft. In this paper, we extend the work to consider events in the historical record with sunspot numbers between 30 and 50. Additionally, we present a new probabilistic model of the absorbed dose due to solar protons at various confidence levels, depths of shielding, and mission durations for periods when SSN < 50.

Background and Motivation

The two most prevalent sources of primary radiation in deep space are galactic cosmic radiation (GCRs) and solar particle events (SPEs). Since SPEs tend to be a greater source of total ionizing dose for short duration missions, the focus of this work is on SPEs. Solar activity tends to follow an eleven-year cycle in which the sun has a higher frequency and more intense SPEs during solar maximum, and a reduced frequency and intensity of SPEs during solar minimum. These phases of solar activity are evident in the Figure 1, which shows the sunspot numbers for recent Solar Cycles and compares the relative rate of big monthly solar-proton fluences. Of the 568 months in the histogram, 38 have a very large accumulation of solar protons, with $>10^7$ protons/cm^2 at >30 MeV. On the other hand, among the 242 months with SSN < 50, only four had such large proton fluences. Thus, the probability of a month with a very large solar proton fluence is roughly four times larger overall than it is during months with SSN <50, i.e., 6.7 $\pm$ 1.0 % versus 1.7 $\pm$ 0.8%.

Methodology

Thirty-nine solar particle events occurred during 1973-2015 with 30 < SSN <50. Of these events, six were Ground Level Events (GLEs), which are extremely energetic SPEs having proton energies above 400 MeV and producing secondary particles that can be observed with ground station neutron monitors on the surface of the Earth. Seven of the events are denoted as sub-GLE events, which produce measureable proton fluxes up to at least 300 MeV but do not produce detectable levels of secondary atmospheric particles. The remaining 26 sub-sub GLEs are even less energetic with an observable increase in protons at energies greater than 30 MeV, but no observable proton flux above 300 MeV. Table 1 gives for each event the four Band fit parameters[2-6] to the event-integrated integral spectrum in rigidity, J(>R). For detailed information on data sources and how we extracted the Band fits, refer to section III in our previous paper[1]. As footnoted in the table, J(>R) in a few of the smaller events is better fit as an exponential, a single power-law, or a so-called Ellison-Ramaty[7] form, which is a single power-law times an exponential. For convenience, Table A1 in the **Appendix (**shown at the end of the paper) provides the spectral fit parameters for events with SSN < 30. Table A1 supercedes the list given in Reference 1, with improved fits for several events and additional sub-sub-GLEs not included in the original study.

We show a few plots of the events in the table above: two each for the GLEs (Figure 2), the sub-GLEs (Figure 3), and the sub-sub-GLEs (Figure 4). The four band fit parameters are shown within each plot. In general, these fits are valid only for proton energies greater than 10 MeV, which is adequate since shielding makes lower-energy protons irrelevant to the radiation hazard for spacecraft electronics. With the large dynamic ranges in these plots, it is difficult to judge visually the goodness of fit. To quantify the goodness of fit, we note in the upper-right corner of each panel the root-mean square (rms) width of the each fit's distribution of fractional residuals, that is, the values of (datum-fit)/datum. For all 90 events in the combined SSN < 50 study, the average rms width is 16.8%. Because of the inherently larger uncertainties in fluences extracted from neutron-monitors, the average rms width for the eight GLEs is 28.4%.

Dose Calculations

We made dose computations with HZETRN 2005, a high-energy particle transport/dose code developed at Langley Research Center[8]. We chose to use the 2005 version of HZETRN for this study due to its ease of use and faster runtimes. We used aluminum as the spacecraft material and considered thicknesses of 1.1, 2, 3, 4, 5, 10, 20, and 50 g/cm^2. The minimum thickness value corresponds to the range of a 10 MeV proton in aluminum. The other values provide a range that will allow interpolations and weighted averages in assessing the performance of realistic shielding distributions. Since we are primarily concerned with non-human missions for this study, we chose a silicon detector to represent sensitive electronics that would be susceptible to total ionizing dose for these types of robotic missions.

For each event, the input to HZETRN is the event-integrated differential fluence (in protons/cm^2-MeV), examples of which are shown in Figures 5 and 6 below. From the integral fluence in rigidity J(>R), the differential fluence in kinetic energy is calculated as $dJ/dE = (dJ/dR)/\beta$, where R is rigidity, E is kinetic energy, and β is the proton speed in units of light-speed.

The compiled results of absorbed dose (cGy [Si]) as a function of aluminum thickness are shown in Table 2. We also highlight the highest dose in green for each thickness represented. Doses for events with SSN < 30 are given in Table A2 in the Appendix. In general, we find the highest doses are produced by GLEs. Therefore, for the case where SSN < 50, the worst-case dose to a thinly shielded spacecraft would be a GLE-type event, based on the historical record. However, there is one sub-GLE (1984 Apr 25) that produces more dose under some shielding depths than three of the GLEs (1977 Sep 24, 1977 Sep 19, and 1973 Apr 29). As shown in Figure 5, the 1984 Apr 25 sub-GLE has a higher fluence than the 1977 Sep 19 GLE until approximately 150 MeV and a higher fluence than the 1973 Apr 29 and 1977 Sep 24 GLEs until approximately 400 MeV[1].

As shown in Figure 6, there are even some sub-sub-GLEs that produce higher doses under light shielding than some GLEs. The 1974 Sep 11 and 2005 Jan 16 sub-sub-GLEs have a higher differential fluence over the 1973 Apr 29 and 1977 Sep 24 GLEs until approximately 60 MeV and 80 MeV, respectively. These higher fluences correlate to the dose results shown in Table 2. Thus, the smaller events cannot be completely discounted and should be included as part of the overall assessment.

When we compare these results with our previous paper, we see that there are more GLEs in the months with 30 < SSN < 50 (six GLEs in 70 months) than in months with SSN < 30 (two GLEs in 173 months). Moreover, the doses from GLEs with 30 < SSN < 50 are generally larger than those with SSN < 30. Higher sunspot number generally correlates with greater solar activity and intensity of events, and our results reflect this tendency.

As noted in the introduction, the standard method of TID estimation has been to use the historical "worst-case SPE" to determine the potential worst-case dose exposure to the vehicle. This worst-case SPE is typically the October 1989 series of events, which contained three GLEs and one energetic storm particle (ESP) event when the

[1] However, it may be worthwhile to note the following: except for the 1984 Apr 25 event, the solar-proton data for events from 1973 November to 1985 December were taken from instruments aboard the IMP-8 spacecraft. IMP-8 had very large gaps in its data recovery during the 1984 Apr 25 event. The spectrum shown here is therefore based on "cleaned" data from the GOES-5 spacecraft, obtained from SPENVIS. Unlike data from subsequent GOES spacecraft, the GOES-5 data are not fully corrected for secondary-response contamination[9].

CME-driven shock reached and washed-over Earth. Table 3 compares the doses for October 1989 to the worst case series of events for SSN < 50, January 2005. Using October 1989 potentially overestimates the dose exposure in a mission undertaken during relative solar quiet conditions, even for shielding thicker than 5.0 g/cm^2, where the October 1989 dose is not dominated by the ESP event. This usage would in turn lead to overdesign of the shielding for the vehicle, increasing the mass and potential cost to the mission.

Probabilistic Modeling of the Solar Proton Radiation Hazard During Periods of Low Solar Activity

We now use these proton fluences and dose calculations to build a probabilistic space radiation hazard model. This model answers questions, such as "Given a mission of N months duration during low solar-activity, what is the probability of accumulating solar proton dose greater than a specified value?" As a technical point, individual events are not the appropriate starting point for a probabilistic model. This fact is easily illustrated by some simple considerations: in 243 months, we have identified 90 potentially significant proton events. This corresponds to a mean rate of $\mu = 90/243 = 0.369$ events/month. With this mean rate, Poisson statistics say that the probability of getting three or more events in one month is 0.62%. For a sample of 243 months, we should expect 1.55 such occurrences. However, our data show 11 months with three or more events. With $\mu = 1.55$, the probability of observing 11 such months is (again, using Poisson statistics) 7.6×10^{-7}. Multi-event months are more frequent than implied by these simple considerations because a given active region moving across the face of the Sun often produces more than one SEP event.

Proper handling of these associations among events requires that we add together events that occur within a specified time interval. This interval should be long enough to group together all events associated with a particular active region, but not so long as to combine episodes likely to be independent. One month is an appropriate time scale for this purpose. As shown in Figure 7, there is no correlation between the solar proton production in a given month and the solar proton production in the preceding month, at least not during periods of low-solar activity.

Thus, the first step in building a probabilistic model is to add together all proton fluences and doses associated with a given month. The 50 months with non-zero SEP quantities derived from our 90 events are listed in Table 4a and 4b for solar proton fluences and absorbed dose, respectively.

For each quantity of interest, we next rank the monthly values in decreasing order. Our study is based on 243 months with SSN < 50. For each month, we therefore evaluate the corresponding cumulative probability, namely (244-r)/244, where r = 1-50 is the rank. A month's rank is not necessarily the same for all quantities of interest. The "month-size" and cumulative probabilities can then be analyzed as log-normal distributions.[10,11] Error! Reference source not found. 8 shows the log-normal distribution for monthly solar proton fluence > 60 MeV (protons/cm^2). The steepening in the distribution at low fluence values below 10^5 protons/cm^2 is likely due to inefficiency in pulling small events out of the GCR and instrumental background. The flattening at the largest fluences is likely due to the small sample of these very large events. In the middle range, the data give a reliable estimate of the log-normal distribution's mean and standard deviations. These general features are true of all of our log-normal plots. Finally, since we start with spectral fits to each of the events in this study, we can generate log-normal fits for any energy threshold of interest. We have produced similar plots for >30 MeV, >100 MeV, >300 MeV, and >500 MeV.

Previous studies of solar particle hazard probabilities have been performed in terms of particle fluence at various energies. However, since we have extracted the proton spectrum for each event, we can calculate the dose due to each event and make a direct probability analysis of dose under various depths of shielding. Figure 9 shows the log-normal distribution of the monthly accumulated solar-proton-dose under 3.0 g/cm^2. The horizontal dashed line represents the dose under 3.0 g/cm^2 from GCRs (all species, not just protons) as calculated from the Badhwar-O'Neill GCR model[12] for the 1977 solar-minimum GCR environment[2]. Figure 9 also shows that there is only a ~5% chance that the accumulated dose due to solar protons will exceed the dose due to GCRs. Similar plots were generated for aluminum shielding values of other thicknesses. The probabilities of GCR- and solar-proton- dose equivalence varied from 10% under 1.1 g/cm^2 to less than 1% under 50 g/cm^2.

[2] It is estimated that the GCR dose in the most recent solar-minimum (~2009) was larger than 1977 by about 20%. (P. M. O'Neill, private communication, 2016)

Probability distributions like those shown in Figures 8 and 9 are sufficient to characterize missions lasting for a single month. But since 1973, there have been four eras with SSN < 50 lasting for 57, 44, 54, and 88 consecutive months, in 1973-1977, 1984-1987, 1993-1998, and 2004-2011, respectively. It is therefore potentially useful to extend this analysis to longer duration missions, particularly if the most recent extended period of SSN <50 represents likely solar behavior for coming decades. Multi-month missions can be addressed by using random-sampling techniques analogous to those in previous studies by Feynman et al. 1993 and Tylka et al. 1997. Specifically, our procedure is as follows:

- For a mission lasting N months, make N independent random samplings from the log-normal distribution.
- Add up these N values to obtain a mission-accumulated value.
- Repeat the above two steps for a large number of trials and rank the results to get the corresponding cumulative probability distribution. In this work, 10^7 trials were performed in order to guarantee a smooth distribution.
- Repeat the above three steps for each quantity of interest.

Figure 10 shows a sample of results from these simulations. The left panel shows the probability of solar-proton dose under 2.0 g/cm^2 Al shielding for mission durations of 1, 2, 3, 5, and 7 years. The right panel shows the probability of solar-proton dose for a one-year mission under Al shielding depths ranging from 1.1 to 50.0 g/cm^2.

Finally, Table 5 shows the upper-limit on the solar-proton dose at confidence levels between 70% and 99% for various depths of shielding and mission durations. Also tabulated are the corresponding GCR doses based on the 1977 solar minimum model.

Comparison to the JPL91 Solar-Proton Fluence Model

Our methodology is inspired by that developed for solar proton fluences in the JPL91 Model[12]. In particular,

- We employ log-normal distributions whose means and standard deviations are derived from observations;
- We use random-sampling techniques to simulate mission-accumulated quantities; and
- We group correlated SEP events together. In our work, we use “months” for this grouping. JPL91 used episodes, many of which last for more than 20 days and hence are analogous to our “months”

However, there are important differences in our approach:

- For each of our events, we extracted the proton spectrum, allowing us to do probabilistic studies for arbitrary proton energy bins as well as doses. JPL91, on the other hand, was constrained to a handful of hardware-defined energy channels;
- In developing the probability rankings, JPL91 counts only the events selected for the study. In our work, based on months, we also count the months in which no SEP significant events were found.
- As a result, JPL91 includes an “events per year” parameter. In JPL91 simulations, the number of events in a trial is sampled from a Poisson distribution with this mean. In our simulations, on the other hand, there are always 12 monthly samplings in each year.
- Most importantly, JPL91 included all SEP events, including those observed during periods of very high solar activity; in our work, we restrict our analysis to events observed during low-activity periods, with SSN < 50.

The similarities between our procedures and those of JPL91 allow us to compare parameters of the data sets and the log-normal distributions. These comparisons are shown in Table 6 for two channels (>30 MeV and >60 MeV) that are featured in both models. We note these differences:

- JPL91 has a higher event rate per month. In our case, this quantity is simply the number of months with significant SEPs (50) divided by the total number of months with SSN <50 (243).

- The mean "event" size is larger by a factor of 10^4 in JPL91.
- The largest "month" in JPL91 is October 1989, whose fluences are nearly an order of magnitude larger than those in the largest month in our survey, January 2005.
- Most important, the slopes of the log-normal distributions (as given by the "Log_{10} Normal Sigma" values) are much larger in our analysis.

This difference in slopes has important implications for the application of our model, as shown in Figure 11. These plots show the log-normal fits from JPL91 (red) and this work (blue) for proton fluences >30 MeV (left) and >60 MeV (right). For probabilities below ~99%, our fluence values fall below those of JPL91, as expected. For very rare fluence levels (>99%) our values are higher than those from JPL91. This is not reasonable. This problem presumably reflects a breakdown of the log-normal distribution at very large fluences, perhaps due to physical limitations on the SEP production.

This problem also affects the mission-accumulated fluences, as illustrated for simulated missions of 1-year duration in Figure 12. For confidence levels above 99% (that is, probabilities below ~1%), our simulated fluence values exceed those from JPL91. This is not reasonable; but it is also not necessarily surprising, in that the historical record is insufficient to address such rare occurrences. *Thus, we conclude that our model results for confidence levels above 99% CL are not reliable and should not be used.*

Discussion

Sunspots, of course, do not cause solar particle events. We simply use them as a general indicator of the level of solar activity, which includes SPEs. As noted, the Sun appears to be moving into a less active regime, with fewer sunspots, fewer and smaller SPEs[14], and decreased coronal and interplanetary magnetic fields[15]. The latter is responsible for the higher GCR levels in the most recent solar-minimum. Shock-acceleration theory also suggests that the weaker fields play a role in the reduction of the SPE radiation-hazard[16].

Our probabilistic calculations are based on the historic record of SPEs during times of low sunspot numbers, derived using data from 20 of the last 43 years of nearly continuous monitoring. One inherent assumption in using our results is that SPE production in future periods of low sunspot number will be no worse than what we have seen so far in the Space Age. This seems likely, but our current understanding of solar activity does not guarantee it.

Utilizing these probabilistic assessments also requires faith in predictions of future solar activity. It may be safe to assume that current low-activity levels will continue for the next year or two. Beyond that, however, is speculative. We have included in our calculations mission durations of 3, 5, and 7 years simply because such calculations have been offered in previous SEP probabilistic models[10,13]. Although the most recent era of SSN < 50 persisted for 88 months (February 2004 - May 2012), whether these extended calculations will be useful depends on future advancements in forecasting solar activity.

In this study, we have focused on a probabilistic model of solar-proton induced dose. But our method of extracting proton spectra offers other opportunities as well. For example, predictions of the total number of a certain type of proton-induced single-event-effects (SEEs) over a mission can also be addressed. To do so, it would be necessary to propagate our solar proton spectra through the shielding distribution, convolve the resulting spectra with the SEE production cross-section to get the number of SEEs (cf. Tylka et al. 1996), and then analyze those results with the same probabilistic procedures we have employed for dose. We note, however, that this work provides no guidance on peak SEE rates, which are also an important engineering consideration.

Finally, as we also have discussed, the October 1989 event sequence has often been used as a plausible worst-case SPE environment. It may therefore be useful to note that the probabilistic dose predictions in this work suggest that there is a ~3-4% probability of encountering an October-1989-like dose level in a one-year mission at SSN < 50 for shielding levels between 1.1 and 50 g/cm^2.

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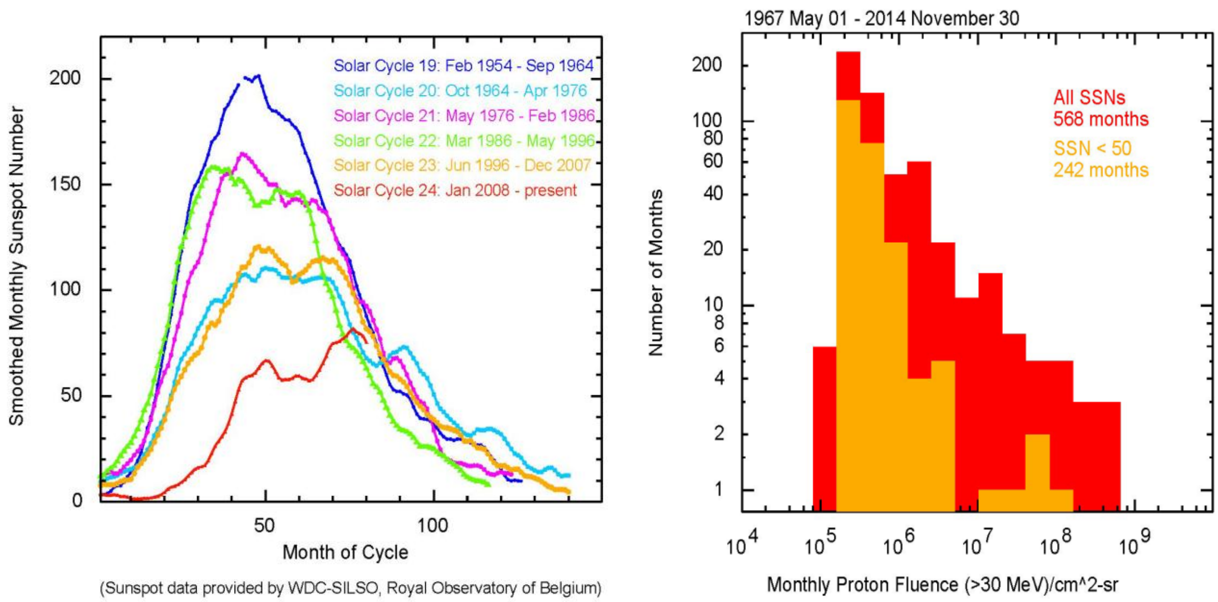

Figure 1: Left: Monthly smoothed sunspot numbers since 1954 plotted versus the month of the Cycle (for Solar Cycles 19-24. Right: Histogram of observed monthly solar-proton fluence above 30 MeV since 1967, with the red histogram representing all months and the gold representing months with SSN <50.

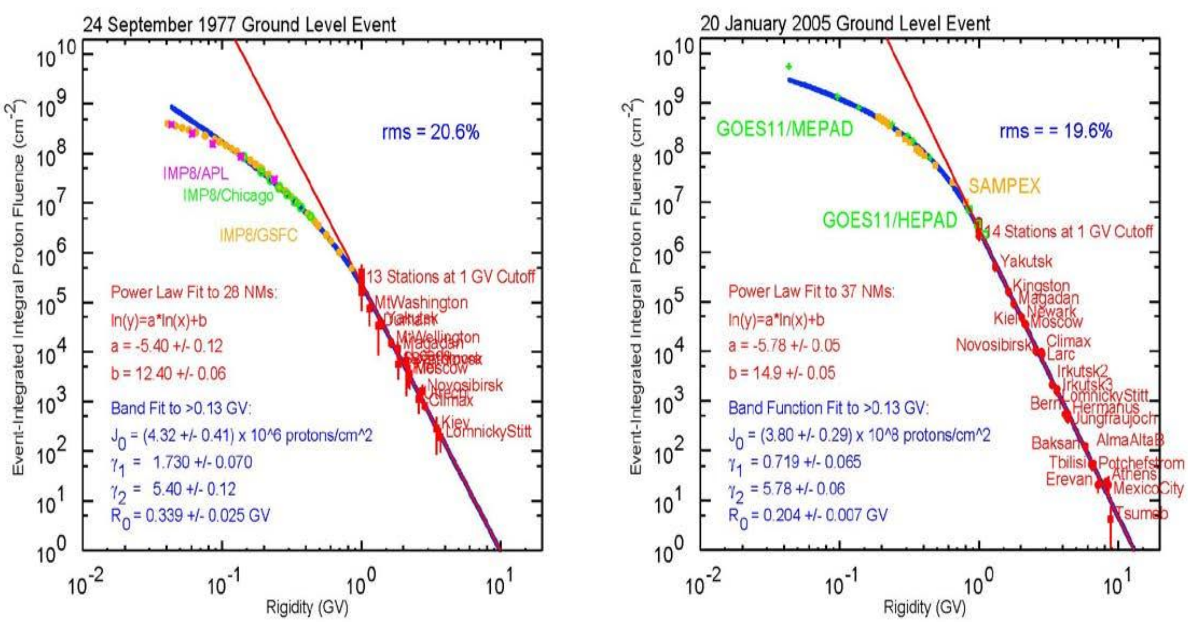

Figure 2: Band function fits to two GLEs. Note that data points at less than 0.13 GV (less than 10 MeV), which are generally irrelevant to dose calculations for spacecraft electronics, are not included in the fits.

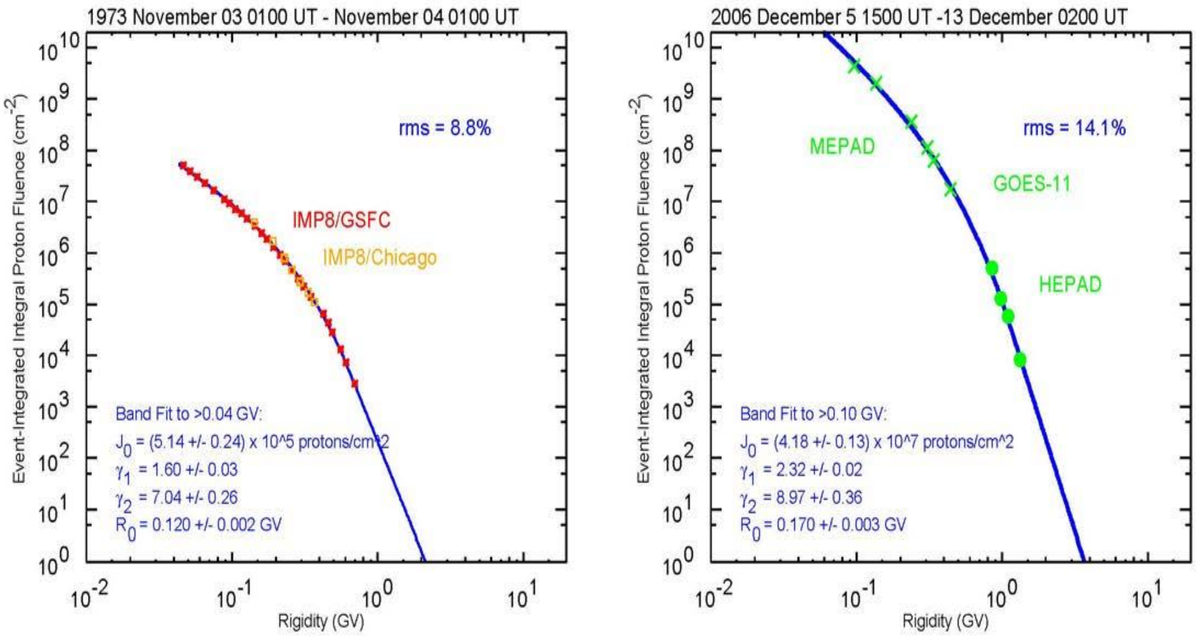

Figure 3: Band function fits to two sub-GLEs.

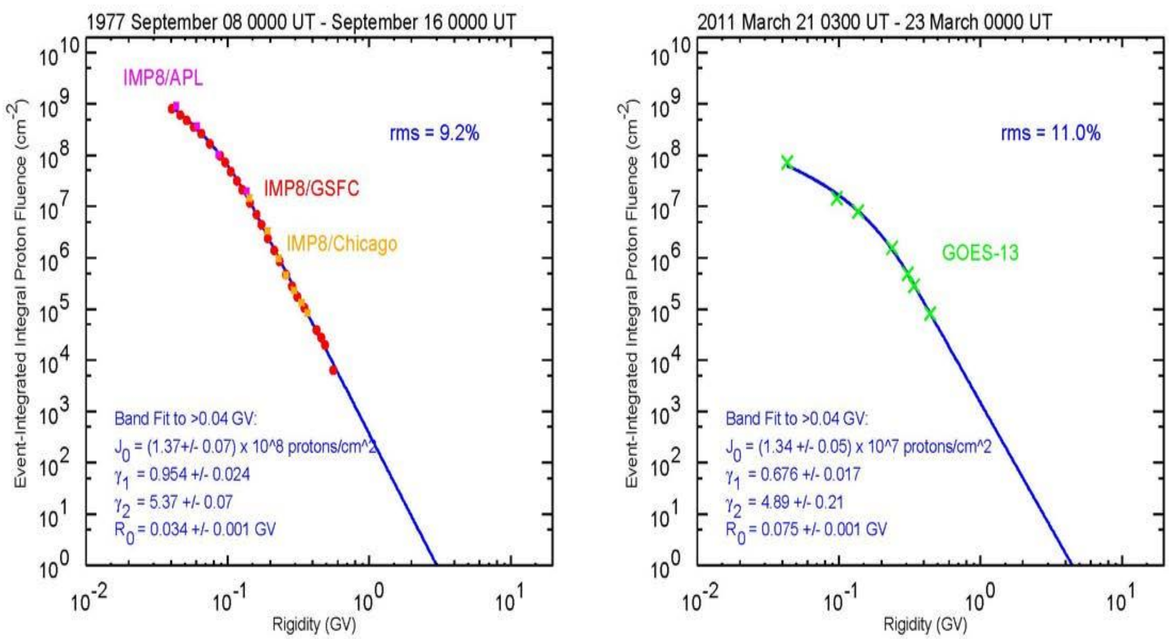

Figure 4: Band function fits to sub-sub-GLEs.

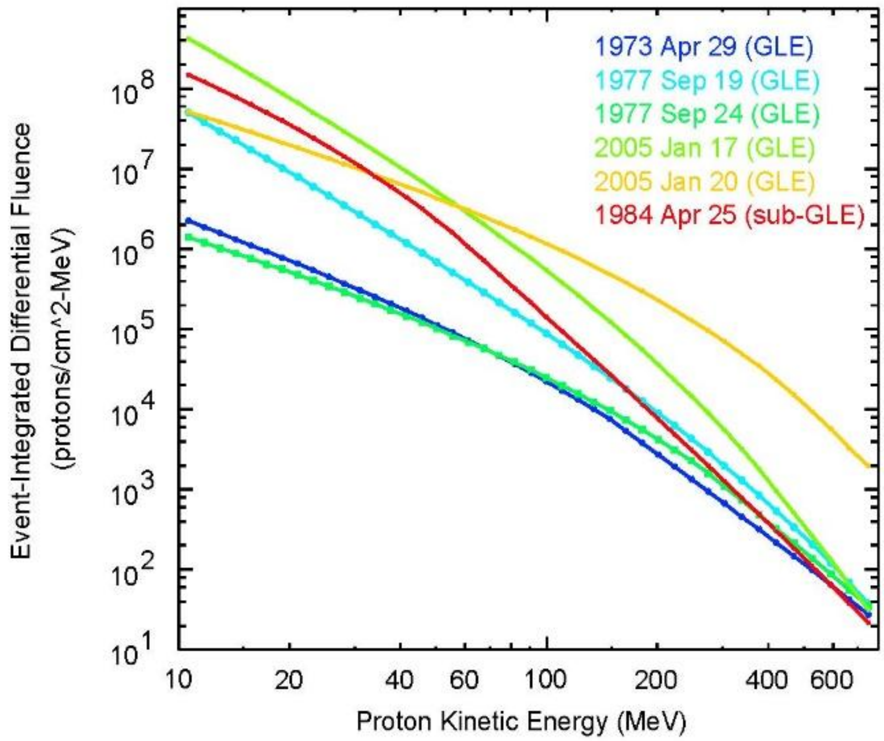

Figure 5: Comparison of several GLEs to a sub-GLE that has greater differential fluence over certain parts of the spectrum.

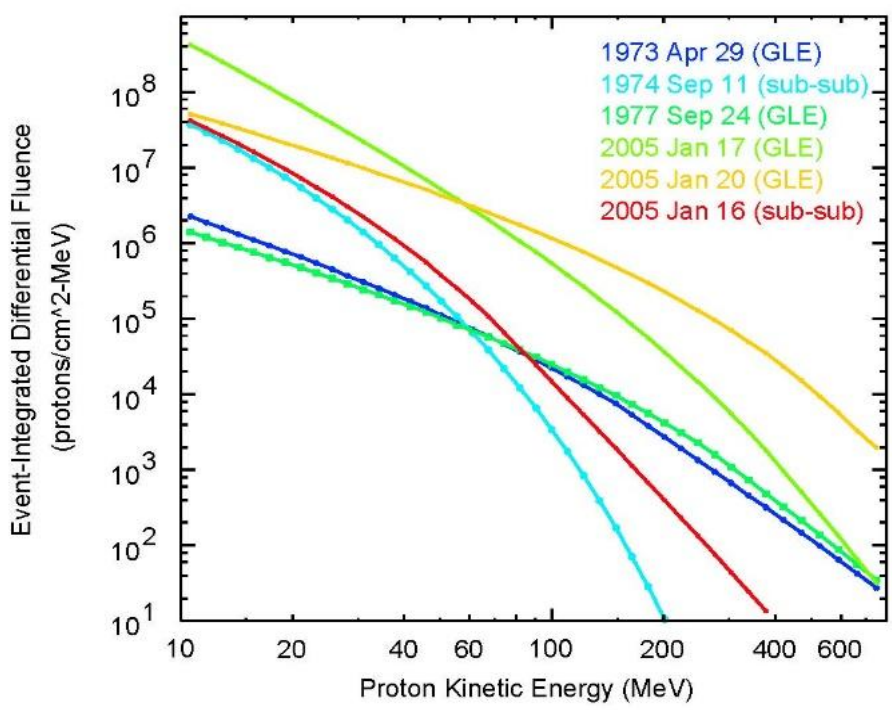

Figure 6: Comparison of several GLEs to two sub-sub-GLEs that have greater differential fluence over certain parts of the spectrum.

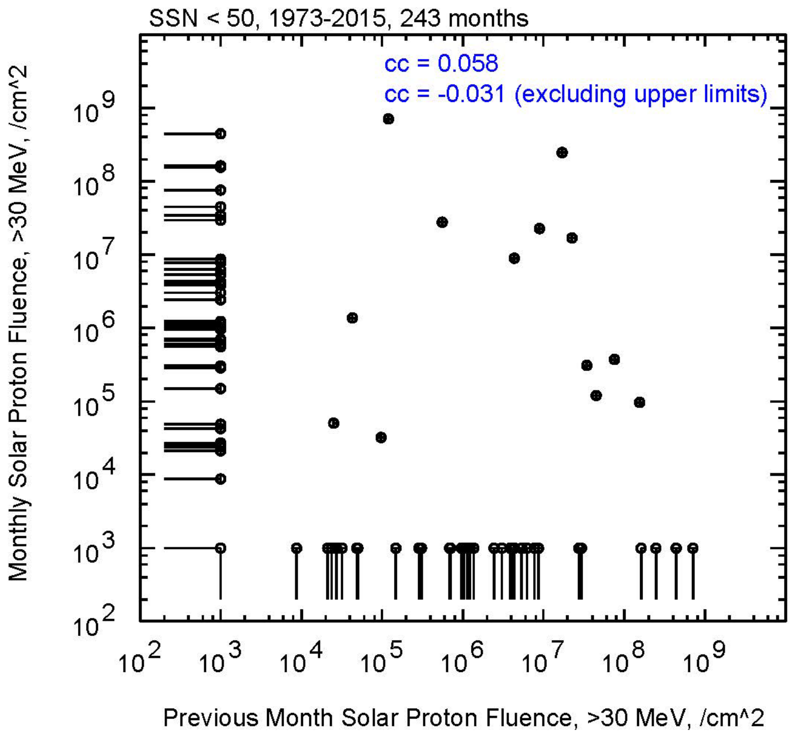

Figure 7: Correlation of monthly solar proton fluence at >30 MeV versus the same quantity in the preceding month. Months for which our search criteria found no significant SEP events are represented here as upper-limits at 1000 protons/cm^2. The correlation coefficients in the upper right indicate that there is no significant correlation, at least for months with SSN < 50.

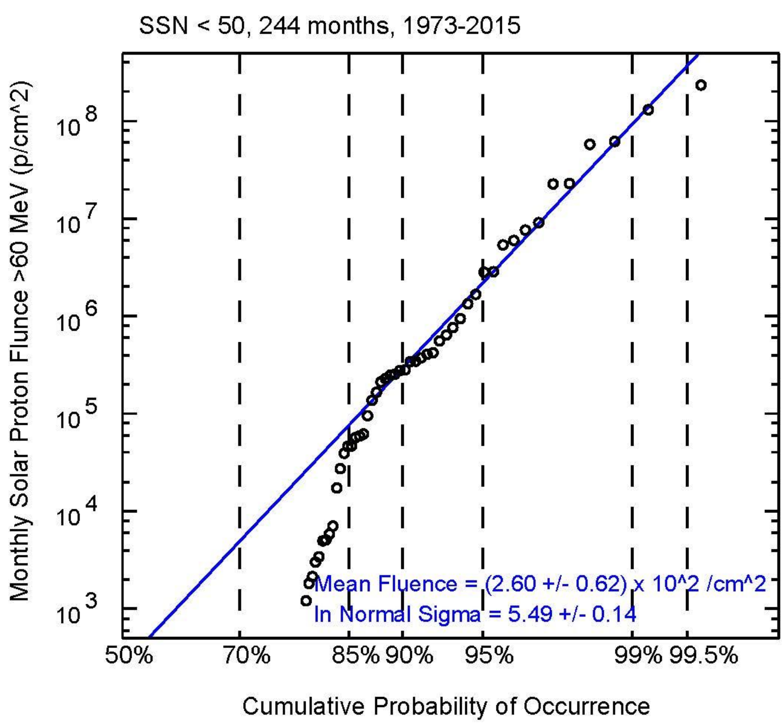

Figure 8: Log-normal fit to the monthly accumulated solar-proton fluence at >60 MeV.

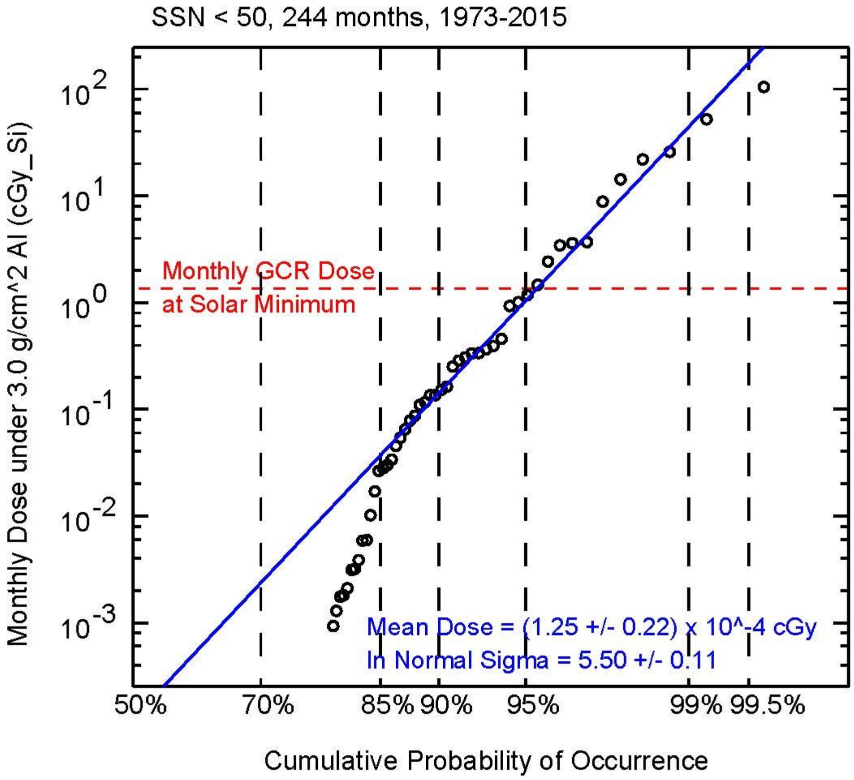

Figure 9: Log-normal fit to the monthly accumulated dose under 3.0 g/cm² of aluminum shielding.

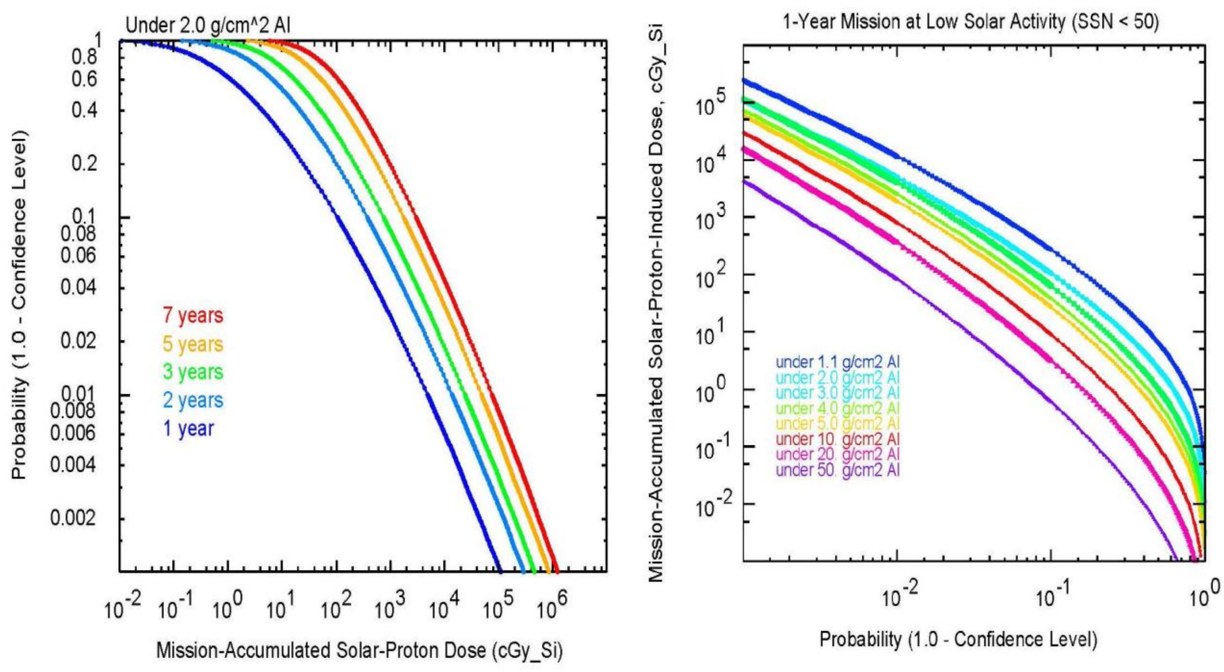

Figure 10: Simulations of accumulated solar-proton dose. Left: probability of dose under 2.0 g/cm² Al shielding for missions durations of 1, 2, 3, 5 and 7 years. Right: Accumulated dose versus probability for a one-year mission under various depths of Al shielding between 1.1 and 50 g/cm².

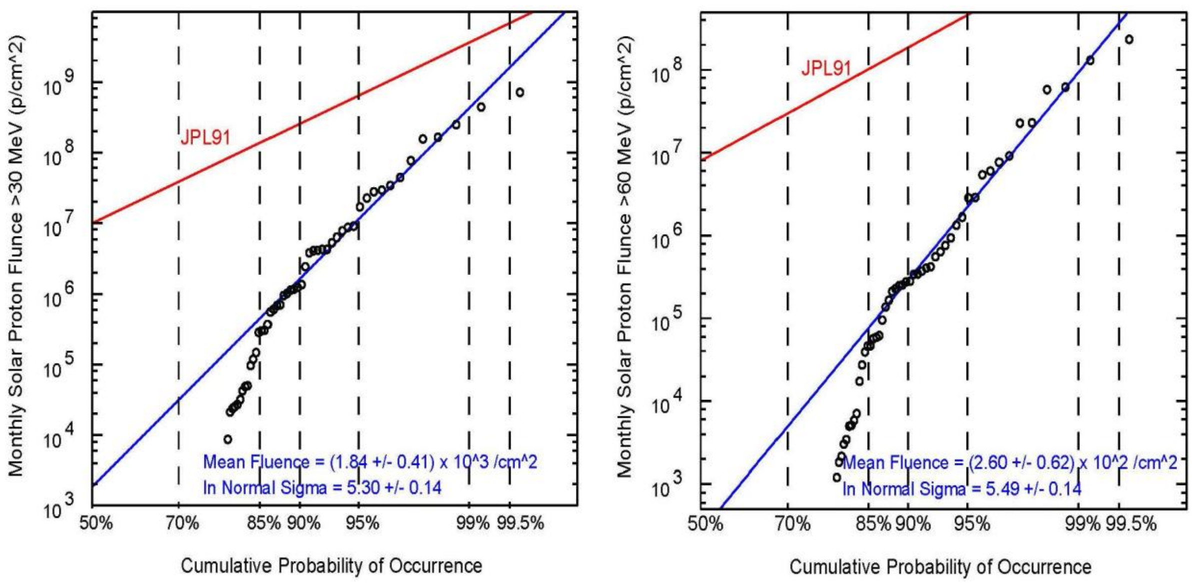

Figure 11: A comparison of the log-normal analysis for monthly solar proton fluences at >30 MeV (left) and >60 MeV (right) in this study (blue) and in the JPL91 model (red).

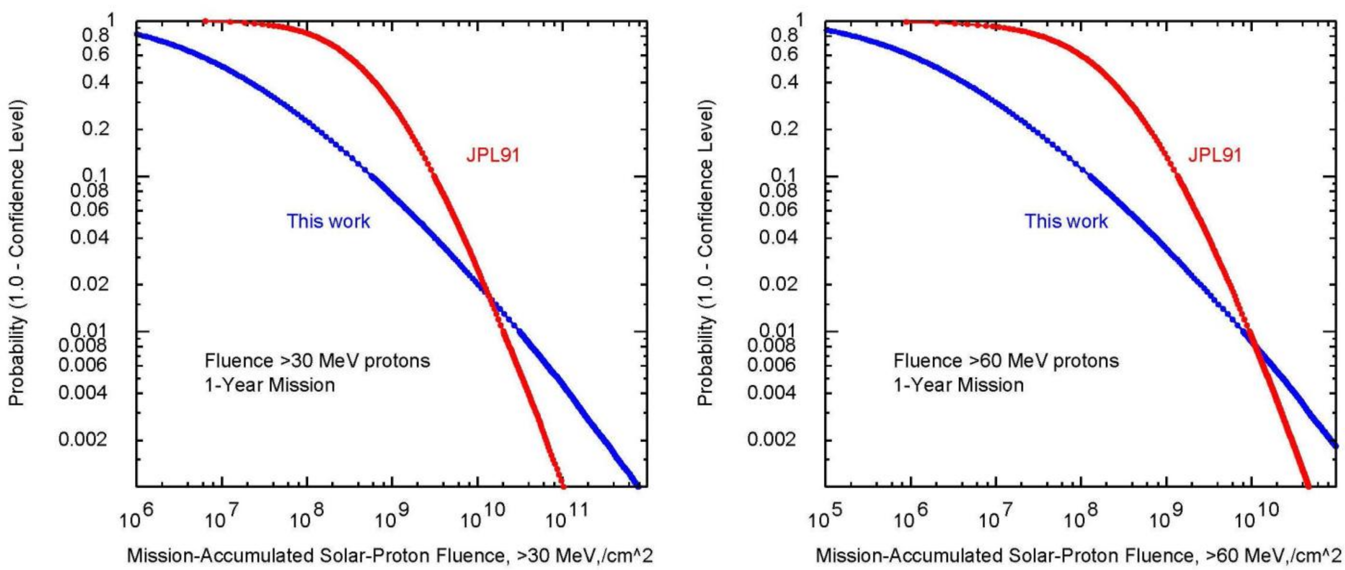

Figure 12: A comparison of probability vs. mission accumulated SEP fluence at >30 MeV (left) and >60 MeV (right) in a 1-year mission from this work (blue) and from the JPL 91 model (red).

Table 1: Spectral-Fit Parameters for Solar Proton Events during Months with 30 < SSN < 50							
Year	Mon	Day	SSN	J_0, p/cm^2	γ_1	γ_2	R_0 (GV)
GLEs							
1973	Apr	29	42.7	7.24E+06	1.073	4.44	0.1628
1977	Sep	19	39.1	1.39E+06	2.995	7.95	0.3163
1977	Sep	24	39.1	4.32E+06	1.730	5.40	0.3390
1997	Nov	06	35.0	8.15E+08	0.284	5.38	0.1159
2005	Jan	17	34.6	3.51E+07	2.649	8.29	0.1619
2005	Jan	20	34.6	3.80E+08	0.719	5.78	0.2040
sub-GLEs							
1973	Nov	02	31.8	5.14E+05	1.597	7.04	0.1196
1974	Sep	19	32.1	1.88E+09	0.830	4.29	0.0253
1974	Sep	24	32.1	9.06E+06	0.780	4.92	0.1817
1984	Apr	25	49.8	4.53E+09	0.513	6.07	0.0582
1997	Nov	04	35.0	5.44E+06	1.354	9.17	0.1567
2004	Nov	01	35.3	1.04E+08	0.278	6.17	0.0680
2004	Nov	10	35.3	2.41E+08	1.130	5.99	0.0647
sub-sub-GLEs							
[a]1973	Sep	7	34.4	1.96E+10	0.000	n/a	0.0272
1974	Jul	3	34.0	1.40E+07	1.906	7.83	0.0448
1974	Jul	5	34.0	1.72E+10	0.403	9.04	0.0287
[a]1974	Sep	11	32.1	9.75E+09	0.000	n/a	0.0368
1977	Sep	08	39.1	1.37E+08	0.954	5.37	0.0339
1977	Sep	17	39.1	4.25E+07	0.928	4.82	0.0587
1977	Oct	12	45.6	6.87E+05	1.686	5.39	0.0789
[b]1984	May	21	47.5	8.33E+04	2.040	n/a	0.0667
[b]1984	May	23	47.5	8.33E+02	5.030	n/a	0.0787
1984	Jun	01	46.5	7.99E+02	3.410	4.90	0.2007
[c]1987	Nov	07	46.7	3.51E+02	5.210	n/a	n/a
1994	Feb	20	34.8	1.16E+07	1.331	4.85	0.0550
[a]1994	Feb	21	34.8	1.66E+11	0.000	n/a	0.0219
2004	Apr	11	45.5	3.83E+08	0.644	6.85	0.0326
2004	Jul	22	40.2	1.67E+04	3.298	5.74	0.1602
2004	Jul	25	40.2	2.04E+09	0.710	8.98	0.0344
[c]2004	Jul	30	40.2	1.05E+03	4.180	n/a	n/a
[a]2004	Sep	13	37.5	3.69E+10	0.000	n/a	0.0250
2004	Sep	19	37.5	1.38E+08	0.374	6.12	0.0533
2004	Nov	07	35.3	1.90E+09	0.787	7.39	0.0372
2004	Dec	3	35.2	1.38E+05	2.027	5.51	0.0782
2005	Jan	15	34.6	5.67E+05	1.584	4.29	0.0966
2005	Jan	16	34.6	1.76E+09	0.505	7.88	0.0490
2011	Jan	28	30.9	2.19E+04	2.217	4.25	0.1883
2011	Mar	07	36.9	1.59E+09	0.200	6.56	0.0358
2011	Mar	21	36.9	1.35E+07	0.676	4.89	0.0746
Alternate functional forms: a=exponential; b=Ellison-Ramaty form; c=power-law							

Table 2: Calculated Absorbed Doses for Solar Proton Events during Months with 30 < SSN < 50										
			Absorbed Dose (cGy) / Thickness of Aluminum Shielding (g/cm^2)							
Year	**Mon**	**Day**	**1.1**	**2**	**3**	**4**	**5**	**10**	**20**	**50**
GLEs										
1973	Apr	29	3.19E+00	1.63E+00	1.01E+00	7.10E-01	5.34E-01	1.59E-01	2.08E-01	6.80E-02
1977	Sept	19	2.44E+01	9.85E+00	5.24E+00	3.34E+00	2.34E+00	7.64E-01	2.20E-01	3.55E-02
1977	Sept	24	1.01E+01	5.18E+00	3.27E+00	2.35E+00	1.81E+00	7.90E-01	3.14E-01	7.85E-02
1997	Nov	06	6.18E+01	3.33E+01	2.11E+01	1.49E+01	1.12E+01	4.26E+00	1.28E+00	1.85E-01
2005	Jan	17	1.95E+02	7.39E+01	3.72E+01	2.26E+01	1.52E+01	4.21E+00	9.57E-01	1.02E-01
2005	Jan	20	1.14E+02	5.08E+01	6.62E+01	3.38E+01	2.69E+01	1.27E+01	5.21E+00	1.24E+00
sub-GLEs										
1973	Nov	02	2.69E-02	1.13E-02	6.30E-03	4.18E-03	3.04E-03	1.15E-03	4.14E-04	1.05E-04
1974	Sep	19	2.49E-01	7.21E-02	3.11E-02	1.72E-02	1.08E-02	2.65E-03	5.97E-04	8.21E-05
1974	Sep	24	2.73E+00	1.53E+00	1.01E+00	7.39E-01	5.77E-01	2.55E-01	9.64E-02	1.98E-02
1984	Apr	25	9.17E+01	3.22E+01	1.44E+01	7.76E+00	4.75E+00	1.05E+00	2.11E-01	2.54E-02
1997	Nov	04	3.64E+00	1.75E+00	1.03E+00	7.02E-01	5.15E-01	1.86E-01	5.56E-02	8.15E-03
2004	Nov	01	2.34E+00	1.00E+00	5.15E-01	3.05E-01	1.99E-01	5.30E-02	1.40E-02	3.00E-03
2004	Nov	10	1.86E+01	6.12E+00	2.65E+00	1.42E+00	8.78E-01	2.00E-01	4.16E-02	5.20E-03
sub-sub-GLEs										
1973	Sep	7	1.95E+00	3.24E-01	8.02E-02	2.71E-02	1.11E-02	7.00E-04	2.00E-04	1.00E-04
1974	Jul	3	7.97E-01	1.71E-01	5.60E-02	2.60E-02	1.40E-02	2.22E-03	3.40E-04	4.00E-05
1974	Jul	5	5.35E-01	1.09E+00	3.11E-01	1.28E-01	6.48E-02	8.40E-03	1.30E-03	2.00E-04
1974	Sep	11	1.21E+01	2.69E+00	8.30E-01	3.51E-01	1.79E-01	2.38E-02	3.18E-03	3.86E-04
1977	Sep	8	5.07E-01	1.32E-01	5.27E-02	2.76E-02	1.67E-02	3.61E-03	7.19E-04	8.72E-05
1977	Sep	17	1.65E+00	5.47E-01	2.58E-01	1.52E-01	1.01E-01	2.86E-02	7.53E-03	1.26E-03
1977	Oct	12	1.80E-02	6.00E-03	3.00E-03	3.00E-03	1.00E-03	2.40E-04	6.00E-05	1.00E-05
1984	May	21	2.85E-02	8.31E-03	3.35E-03	1.70E-03	9.76E-04	1.54E-04	1.72E-05	1.17E-06
1984	May	23	4.46E-02	8.39E-03	2.54E-03	1.06E-03	5.24E-04	5.78E-05	7.33E-06	1.35E-06
1984	Jun	01	1.87E-02	6.50E-03	3.10E-03	1.80E-03	1.20E-03	3.00E-04	1.00E-04	1.00E-05
1987	Nov	07	3.83E-01	1.19E-01	5.35E-02	3.05E-02	1.98E-02	5.22E-03	1.27E-03	1.92E-04
1994	Feb	20	5.30E-02	1.70E-02	8.00E-03	5.00E-03	3.00E-03	9.00E-04	2.00E-04	4.00E-05
1994	Feb	21	3.07E+00	3.39E-01	6.10E-02	1.65E-02	5.77E-03	5.93E-04	3.22E-04	9.86E-05
2004	Apr	11	5.19E-01	1.21E-01	4.50E-02	2.21E-02	1.28E-02	2.45E-03	4.40E-04	4.90E-05
2004	Jul	22	7.30E-02	3.10E-02	1.70E-02	1.09E-02	7.68E-03	2.48E-03	7.40E-04	1.50E-04
2004	Jul	25	4.39E+00	8.73E-01	2.55E-01	1.06E-01	5.40E-02	6.92E-03	9.60E-04	1.30E-04
2004	Jul	30	2.11E-01	8.00E-02	4.20E-02	2.60E-02	1.83E-02	6.13E-03	1.94E-03	4.10E-04
2004	Sep	13	2.42E+00	3.42E-01	7.47E-02	2.32E-02	8.81E-03	5.63E-04	2.00E-04	6.30E-05
2004	Sep	19	1.62E+00	5.43E-01	2.33E-01	1.23E-01	7.50E-02	1.64E-02	3.27E-03	3.90E-04
2004	Nov	7	5.83E-01	1.27E-01	4.40E-02	2.10E-02	1.20E-02	2.00E-03	3.00E-04	4.00E-05
2004	Dec	3	7.35E-02	2.33E-02	1.01E-02	5.61E-03	3.55E-03	8.78E-04	2.00E-04	2.77E-05
2005	Jan	15	2.49E-01	9.40E-02	4.70E-02	2.92E-02	2.00E-02	6.32E-03	1.87E-03	3.60E-04
2005	Jan	16	1.80E+01	5.48E+00	2.22E+00	1.11E+00	6.18E-01	9.60E-02	1.36E-02	1.30E-03
2011	Jan	28	7.28E-02	3.09E-02	1.70E-02	1.09E-02	7.68E-03	2.48E-03	7.41E-04	1.46E-04
2011	Mar	07	1.95E+00	4.79E-01	1.83E-01	9.31E-02	5.50E-02	1.11E-02	2.05E-03	2.30E-04
2011	Mar	21	7.69E-01	3.08E-01	1.53E-01	9.05E-02	5.97E-02	1.67E-02	4.34E-03	7.05E-04

				Thickness Al (g/cm^2) / Absorbed Dose (cGy {Si})							
Start Date			Event Type	1.1	2	3	4	5	10	20	50
1989	Oct	19	GLE	214.0	122.0	81.6	60.4	47.3	20.9	7.84	1.54
1989	Oct	20	ESP	1022.0	415.3	211.2	128.6	87.4	26.9	7.73	1.44
1989	Oct	22	GLE	489.0	231.0	134.0	89.6	64.7	22.1	6.12	0.78
1989	Oct	24	GLE	230.0	110.0	66.4	46.1	34.7	14.1	5.22	1.21
1989	Oct	Total		1955.0	878.3	493.2	324.7	234.1	84.0	26.9	4.97
2005	Jan	15	sub-sub	0.25	0.094	0.047	0.029	0.020	0.0063	0.0019	0.0004
2005	Jan	16	sub-sub	18.0	5.5	2.2	1.1	0.618	0.096	0.0136	0.0013
2005	Jan	17	GLE	195.0	73.9	37.2	22.6	15.2	4.21	0.957	0.102
2005	Jan	20	GLE	114.0	50.8	66.2	33.8	26.9	12.7	5.21	1.24
2005	Jan	Total		327.2	130.3	105.7	56.4	42.1	16.9	6.17	1.34
Ratio: October 1989 / January 2005:				5.97	6.74	4.67	5.76	5.56	4.97	4.36	3.70

Table 3: Accumulated Solar-Proton Dose in October 1989 and January 2005

Table 4a: Monthly-Accumulated Solar Proton Fluences During Months with SSN < 50

	Year	Month	SSN	Monthly Solar Proton Fluence, cm^-2				
				>30 MeV	>60 MeV	>100 MeV	>300 MeV	>500 MeV
1	1973	Apr	42.7	7.81E+06	2.86E+06	1.14E+06	8.62E+04	2.28E+04
2	1973	Sep	34.4	3.04E+06	7.25E+04	1.55E+03	2.33E-03	8.07E-08
3	1973	Nov	31.8	6.92E+05	1.68E+05	4.64E+04	9.85E+02	1.19E+02
4	1974	Jul	34.0	8.62E+06	3.77E+05	3.65E+04	2.05E+02	1.59E+01
5	1974	Sep	32.1	2.98E+07	5.45E+06	2.00E+06	1.62E+05	3.86E+04
6	1974	Nov	27.5	2.46E+06	6.47E+05	1.95E+05	5.31E+03	6.50E+02
7	1975	Aug	14.3	1.24E+06	3.49E+05	1.02E+05	3.08E+03	5.12E+02
8	1975	Nov	16.1	2.13E+04	3.03E+03	7.04E+02	2.63E+01	5.06E+00
9	1976	Mar	12.2	5.63E+05	2.51E+05	1.47E+05	4.88E+04	2.83E+04
10	1976	Apr	12.1	2.77E+07	9.24E+06	3.54E+06	2.18E+05	3.48E+04
11	1976	Aug	14.0	1.03E+06	2.12E+05	4.77E+04	4.19E+02	2.80E+01
12	1977	Sep	39.1	7.70E+07	2.29E+07	8.85E+06	8.00E+05	1.89E+05
13	1977	Oct	45.6	3.76E+05	5.98E+04	1.43E+04	5.70E+02	1.13E+02
14	1984	Apr	49.8	1.58E+08	2.32E+07	4.62E+06	1.23E+05	1.99E+04
15	1984	May	47.5	9.84E+04	7.17E+03	7.50E+02	8.26E-01	6.42E-03
16	1984	Jun	46.5	3.24E+04	5.91E+03	1.61E+03	8.60E+01	1.98E+01
17	1985	Jan	20.5	1.19E+06	2.79E+05	7.08E+04	8.30E+02	5.22E+01
18	1985	Apr	18.3	4.32E+06	7.70E+05	1.96E+05	6.35E+03	8.72E+02
19	1985	Jul	17.4	3.89E+06	1.36E+06	6.25E+05	1.45E+05	8.42E+04
20	1986	Feb	13.1	3.47E+07	7.70E+06	2.22E+06	6.87E+04	6.87E+03
21	1986	Mar	13.0	3.08E+05	4.68E+04	8.73E+03	1.75E+02	2.47E+01
22	1986	May	14.3	9.64E+05	2.86E+05	1.03E+05	1.62E+04	8.02E+03
23	1987	May	26.5	2.76E+04	2.17E+03	2.01E+02	1.03E-01	4.11E-04
24	1987	Nov	46.7	6.10E+05	9.68E+04	2.44E+04	1.10E+03	2.31E+02
25	1994	Feb	34.8	4.24E+06	2.30E+05	5.55E+04	3.04E+03	7.11E+02
26	1994	Jul	28.5	2.41E+04	1.22E+03	5.84E+01	1.37E-03	3.48E-07
27	1994	Sep	26.6	4.31E+04	5.00E+03	9.86E+02	2.56E+01	4.10E+00
28	1994	Oct	28.9	1.38E+06	2.59E+05	6.68E+04	3.27E+03	7.24E+02
29	1995	Apr	20.6	8.82E+03	1.82E+03	4.42E+02	5.95E+00	2.90E-01
30	1995	Oct	12.1	1.15E+06	1.37E+05	2.75E+04	7.39E+02	1.21E+02
31	1997	Apr	16.5	2.53E+04	3.44E+03	6.97E+02	1.98E+01	3.65E+00
32	1997	May	18.3	5.07E+04	5.09E+03	6.37E+02	5.80E+00	5.50E-01
33	1997	Sep	28.3	4.90E+04	2.77E+04	1.81E+04	6.90E+03	4.26E+03
34	1997	Nov	35.0	1.65E+08	6.18E+07	2.34E+07	1.13E+06	2.23E+05
35	2004	Apr	45.5	7.05E+05	6.21E+04	1.01E+04	1.68E+02	2.15E+01
36	2004	Jul	40.2	6.37E+06	4.27E+05	7.29E+04	3.63E+03	1.00E+03
37	2004	Sep	37.5	5.37E+06	4.09E+05	7.21E+04	1.84E+03	2.94E+02
38	2004	Nov	35.3	4.50E+07	6.04E+06	1.18E+06	3.09E+04	5.02E+03
39	2004	Dec	35.2	1.20E+05	1.75E+04	4.04E+03	1.50E+02	2.88E+01
40	2005	Jan	34.6	7.21E+08	2.34E+08	9.78E+07	9.01E+06	1.79E+06
41	2005	May	28.9	4.32E+06	3.47E+05	5.87E+04	1.31E+03	2.03E+02
42	2005	Jun	28.8	9.09E+06	2.90E+06	9.38E+05	6.92E+04	1.87E+04
43	2005	Jul	29.1	2.28E+07	1.68E+06	1.82E+05	1.52E+03	1.48E+02
44	2005	Aug	27.4	1.70E+07	9.43E+05	8.56E+04	3.88E+02	2.59E+01
45	2005	Sep	25.8	2.49E+08	5.84E+07	1.84E+07	9.31E+05	1.79E+05
46	2006	Jul	15.2	2.90E+05	5.77E+04	1.56E+04	8.25E+02	1.89E+02
47	2006	Dec	12.1	4.48E+08	1.31E+08	4.61E+07	2.37E+06	3.71E+05
48	2010	Aug	17.4	3.06E+05	4.73E+04	1.14E+04	4.70E+02	9.48E+01
49	2011	Jan	30.9	1.49E+05	3.96E+04	1.30E+04	1.02E+03	2.86E+02
50	2011	Mar	36.9	4.19E+06	5.66E+05	1.28E+05	5.32E+03	1.14E+03

Table 4b: Monthly-Accumulated Absorbed Dose due to Solar Protons during Months with SSN < 50										
	Year	**Month**	**Dose from Solar Protons, cGy (Si), under depths of Aluminum shielding**							
			1.1 g/cm2	**2 g/cm2**	**3 g/cm2**	**4 g/cm2**	**5 g/cm2**	**10 g/cm2**	**20 g/cm2**	**50 g/cm2**
1	1973	Apr	3.19E+00	1.63E+00	1.01E+00	7.10E-01	5.34E-01	1.59E-01	2.08E-01	6.80E-02
2	1973	Sep	1.95E+00	3.24E-01	8.02E-02	2.71E-02	1.11E-02	7.00E-04	2.00E-04	1.00E-04
3	1973	Nov	3.47E-01	1.46E-01	7.82E-02	4.92E-02	3.39E-02	9.87E-03	2.26E-03	2.24E-04
4	1974	Jul	1.33E+00	1.26E+00	3.67E-01	1.54E-01	7.88E-02	1.06E-02	1.64E-03	2.40E-04
5	1974	Sep	1.82E+01	5.43E+00	2.45E+00	1.47E+00	1.01E+00	3.60E-01	1.24E-01	2.49E-02
6	1974	Nov	1.20E+00	5.17E-01	2.84E-01	1.83E-01	1.28E-01	4.00E-02	1.01E-02	1.16E-03
7	1975	Aug	5.75E-01	2.67E-01	1.51E-01	9.87E-02	6.96E-02	2.13E-02	5.01E-03	5.96E-04
8	1975	Nov	1.37E-02	4.03E-03	1.75E-03	9.72E-04	6.16E-04	1.53E-04	3.49E-05	4.88E-06
9	1976	Mar	2.13E-01	1.05E-01	6.55E-02	4.77E-02	3.77E-02	1.91E-02	9.94E-03	4.27E-03
10	1976	Apr	1.21E+01	5.78E+00	3.43E+00	2.35E+00	1.74E+00	6.54E-01	2.12E-01	3.69E-02
11	1976	Aug	5.42E-01	2.16E-01	1.10E-01	6.63E-02	4.39E-02	1.10E-02	2.01E-03	1.39E-04
12	1977	Sep	3.67E+01	1.57E+01	8.82E+00	5.87E+00	4.27E+00	1.59E+00	5.42E-01	1.15E-01
13	1977	Oct	2.21E-01	7.52E-02	3.38E-02	1.90E-02	1.21E-02	3.06E-03	7.13E-04	1.02E-04
14	1984	Apr	9.17E+01	3.22E+01	1.44E+01	7.76E+00	4.75E+00	1.05E+00	2.11E-01	2.54E-02
15	1984	May	7.31E-02	1.67E-02	5.89E-03	2.76E-03	1.50E-03	2.12E-04	2.45E-05	2.52E-06
16	1984	Jun	1.87E-02	6.50E-03	3.10E-03	1.80E-03	1.20E-03	3.00E-04	1.00E-04	1.00E-05
17	1985	Jan	5.98E-01	2.53E-01	1.35E-01	8.39E-02	5.72E-02	1.57E-02	3.23E-03	2.56E-04
18	1985	Apr	2.58E+00	8.50E-01	3.95E-01	2.29E-01	1.50E-01	3.95E-02	9.24E-03	1.20E-03
19	1985	Jul	1.69E+00	7.78E-01	4.56E-01	3.12E-01	2.33E-01	9.52E-02	3.91E-02	1.30E-02
20	1986	Feb	1.86E+01	7.08E+00	3.62E+00	2.24E+00	1.53E+00	4.56E-01	1.16E-01	1.45E-02
21	1986	Mar	1.83E-01	6.17E-02	2.80E-02	1.57E-02	9.76E-03	2.06E-03	3.74E-04	4.04E-05
22	1986	May	4.39E-01	2.03E-01	1.16E-01	7.57E-02	5.38E-02	1.80E-02	6.06E-03	1.69E-03
23	1987	May	1.95E-02	4.96E-03	1.80E-03	8.46E-04	4.56E-04	5.82E-05	5.59E-06	5.64E-07
24	1987	Nov	3.83E-01	1.19E-01	5.35E-02	3.05E-02	1.98E-02	5.22E-03	1.27E-03	1.92E-04
25	1994	Feb	3.73E+00	5.57E-01	1.64E-01	7.67E-02	4.56E-02	1.19E-02	3.27E-03	5.87E-04
26	1994	Jul	1.81E-02	4.07E-03	1.29E-03	5.28E-04	2.51E-04	2.00E-05	1.73E-06	3.99E-07
27	1994	Sep	2.85E-02	7.91E-03	3.19E-03	1.69E-03	1.03E-03	2.26E-04	4.54E-05	5.52E-06
28	1994	Oct	7.81E-01	2.79E-01	1.35E-01	7.92E-02	5.19E-02	1.39E-02	3.46E-03	5.42E-04
29	1995	Apr	4.73E-03	1.83E-03	9.25E-04	5.60E-04	3.73E-04	9.81E-05	2.01E-05	1.73E-06
30	1995	Oct	7.55E-01	2.14E-01	8.70E-02	4.62E-02	2.82E-02	6.27E-03	1.28E-03	1.57E-04
31	1997	Apr	1.63E-02	4.85E-03	2.09E-03	1.14E-03	7.07E-04	1.58E-04	3.17E-05	3.96E-06
32	1997	May	3.29E-02	9.68E-03	3.84E-03	1.90E-03	1.05E-03	1.64E-04	2.34E-05	2.24E-06
33	1997	Sep	1.46E-02	8.52E-03	5.96E-03	4.65E-03	3.84E-03	2.17E-03	1.22E-03	5.63E-04
34	1997	Nov	6.54E+01	3.51E+01	2.21E+01	1.56E+01	1.17E+01	4.45E+00	1.34E+00	1.93E-01
35	2004	Apr	5.19E-01	1.21E-01	4.50E-02	2.21E-02	1.28E-02	2.45E-03	4.40E-04	4.90E-05
36	2004	Jul	4.86E+00	1.04E+00	3.37E-01	1.55E-01	8.68E-02	1.65E-02	3.65E-03	6.38E-04
37	2004	Sep	4.04E+00	8.85E-01	3.08E-01	1.46E-01	8.38E-02	1.70E-02	3.47E-03	4.53E-04
38	2004	Nov	2.83E+01	8.72E+00	3.72E+00	1.99E+00	1.22E+00	2.78E-01	5.97E-02	8.65E-03
39	2004	Dec	7.35E-02	2.33E-02	1.01E-02	5.61E-03	3.55E-03	8.78E-04	2.00E-04	2.77E-05
40	2005	Jan	3.27E+02	1.30E+02	1.06E+02	5.75E+01	4.27E+01	1.70E+01	6.18E+00	1.34E+00
41	2005	May	3.34E+00	7.06E-01	2.52E-01	1.24E-01	7.16E-02	1.41E-02	2.77E-03	3.60E-04
42	2005	Jun	3.86E+00	1.97E+00	1.18E+00	7.93E-01	5.68E-01	1.81E-01	5.28E-02	1.00E-02
43	2005	Jul	1.58E+01	4.15E+00	1.47E+00	6.60E-01	3.45E-01	4.86E-02	6.76E-03	7.27E-04
44	2005	Aug	1.26E+01	2.91E+00	9.25E-01	3.85E-01	1.93E-01	2.44E-02	3.15E-03	3.93E-04
45	2005	Sep	1.31E+02	5.04E+01	2.62E+01	1.64E+01	1.14E+01	3.64E+00	1.02E+00	1.61E-01
46	2006	Jul	1.55E-01	6.07E-02	2.99E-02	1.75E-02	1.15E-02	3.20E-03	8.23E-04	1.33E-04
47	2006	Dec	2.11E+02	9.31E+01	5.25E+01	3.47E+01	2.50E+01	8.78E+00	2.66E+00	4.21E-01
48	2010	Aug	1.84E-01	5.98E-02	2.65E-02	1.49E-02	9.56E-03	2.45E-03	5.76E-04	8.33E-05
49	2011	Jan	7.28E-02	3.09E-02	1.70E-02	1.09E-02	7.68E-03	2.48E-03	7.41E-04	1.46E-04
50	2011	Mar	2.72E+00	7.87E-01	3.36E-01	1.84E-01	1.15E-01	2.78E-02	6.39E-03	9.35E-04

Table 5: Model Parameters for JPL91 and This Work								
	>30 MeV				>60 MeV			
	Average Rate, Events/month	Log_{10} Normal Sigma	Mean Event Size, p/cm^2	Largest Event in Sample, p/cm^2	Average Rate, Events/month	Log_{10} Normal Sigma	Mean Event Size, p/cm^2	Largest Event in Sample, p/cm^2
JPL91	0.60	1.10	1.00E+07	5.02E+09	0.39	1.07	8.00E+06	2.69E+09
This Work	0.21	2.30	1.84E+03	7.21E+08	0.21	2.38	2.60E+02	2.34E+08

Table 6: Upper Limits on Solar-Proton-Induced Dose (cGy) in Years with SSN < 50						
(Values in red exceed the GCR-Induced Dose)						
Depth of Shielding (Al)	Confidence Level	1 Year	2 Years	3 Years	5 Years	7 Years
1.1 g/cm2	70%	2.65E+01	1.16E+02	2.59E+02	6.73E+02	1.23E+03
	80%	6.73E+01	2.65E+02	5.66E+02	1.40E+03	2.46E+03
	90%	2.70E+02	9.40E+02	1.89E+03	4.31E+03	7.25E+03
	95%	9.36E+02	2.95E+03	5.65E+03	1.21E+04	1.97E+04
	99%	1.17E+04	3.23E+04	5.67E+04	1.08E+05	1.68E+05
	GCR	16.32	32.64	48.96	81.6	114.24
2.0 g/cm2	70%	9.74E+00	4.40E+01	9.94E+01	2.64E+02	4.86E+02
	80%	2.53E+01	1.03E+02	2.21E+02	5.59E+02	9.94E+02
	90%	1.05E+02	3.76E+02	7.55E+02	1.78E+03	3.02E+03
	95%	3.75E+02	1.21E+03	2.31E+03	5.17E+03	8.47E+03
	99%	4.94E+03	1.40E+04	2.43E+04	4.92E+04	7.68E+04
	GCR	16.32	32.64	48.96	81.6	114.24
3.0 g/cm2	70%	4.86E+00	2.42E+01	5.80E+01	1.65E+02	3.18E+02
	80%	1.37E+01	6.08E+01	1.40E+02	3.74E+02	6.95E+02
	90%	6.36E+01	2.49E+02	5.30E+02	1.31E+03	2.33E+03
	95%	2.50E+02	8.76E+02	1.78E+03	4.16E+03	7.09E+03
	99%	4.03E+03	1.20E+04	2.24E+04	4.73E+04	7.58E+04
	GCR	16.32	32.64	48.96	81.6	114.24
4.0 g/cm2	70%	2.83E+00	1.43E+01	3.46E+01	9.98E+01	1.94E+02
	80%	8.05E+00	3.64E+01	8.43E+01	2.28E+02	4.27E+02
	90%	3.81E+01	1.51E+02	3.25E+02	8.09E+02	1.46E+03
	95%	1.53E+02	5.41E+02	1.10E+03	2.58E+03	4.48E+03
	99%	2.53E+03	7.62E+03	1.44E+04	2.99E+04	4.98E+04
	GCR	16.32	32.64	48.96	81.6	114.24
5.0 g/cm2	70%	1.91E+00	9.90E+00	2.45E+01	7.13E+01	1.39E+02
	80%	5.53E+00	2.56E+01	6.03E+01	1.66E+02	3.12E+02
	90%	2.69E+01	1.09E+02	2.39E+02	6.07E+02	1.08E+03
	95%	1.10E+02	3.99E+02	8.25E+02	1.97E+03	3.40E+03
	99%	1.92E+03	5.88E+03	1.12E+04	2.36E+04	3.88E+04
	GCR	16.32	32.64	48.96	81.6	114.24
10 g/cm2	70%	5.50E-01	3.11E+00	7.99E+00	2.47E+01	4.99E+01
	80%	1.70E+00	8.56E+00	2.07E+01	6.03E+01	1.17E+02
	90%	9.02E+00	3.92E+01	8.90E+01	2.38E+02	4.39E+02
	95%	3.99E+01	1.56E+02	3.28E+02	8.35E+02	1.48E+03
	99%	8.11E+02	2.66E+03	5.12E+03	1.16E+04	1.98E+04
	GCR	16.08	32.16	48.24	80.4	112.56
20 g/cm2	70%	1.72E-01	1.05E+00	2.83E+00	9.11E+00	1.92E+01
	80%	5.62E-01	3.06E+00	7.73E+00	2.34E+01	4.74E+01
	90%	3.26E+00	1.52E+01	3.59E+01	9.90E+01	1.92E+02
	95%	1.56E+01	6.48E+01	1.42E+02	3.70E+02	6.85E+02
	99%	3.68E+02	1.28E+03	2.56E+03	5.85E+03	1.01E+04
	GCR	15.48	30.96	46.44	77.4	108.36
50 g/cm2	70%	2.82E-02	1.84E-01	5.14E-01	1.75E+00	3.82E+00
	80%	9.71E-02	5.63E-01	1.48E+00	4.68E+00	9.87E+00
	90%	6.08E-01	3.00E+00	7.36E+00	2.12E+01	4.23E+01
	95%	3.11E+00	1.37E+01	3.12E+01	8.51E+01	1.61E+02
	99%	8.40E+01	3.01E+02	6.35E+02	1.50E+03	2.68E+03
	GCR	14.16	28.32	42.48	70.8	99.12

Appendix

Table A1 contains spectral fit parameters for solar proton events that occurred when SSN < 30. This is an update of the results from Reference 1, with some revised fit parameters and additional sub-sub-GLEs that were not included in the original listing. Table A2 contains the corresponding calculated doses for these events.

Table A1: Spectral-Fit Parameters for Solar Proton Events during Months with SSN < 30

Year	Mon	Day	SSN	J_0, p/cm^2	γ_1	γ_2	R_0 (GV)
GLEs							
1976	Apr	30	12.1	7.62E+06	1.710	6.33	0.2054
2006	Dec	13	23.0	1.33E+08	1.045	5.80	0.1765
sub-GLEs							
1974	Nov	05	27.5	1.18E+06	1.705	7.01	0.1390
1975	Aug	21	14.3	8.02E+05	0.958	8.83	0.1035
1975	Aug	22	14.3	4.38E+06	0.605	5.74	0.0978
1976	Aug	22	14.0	2.85E+06	1.182	9.03	0.0877
1985	Jan	22	20.5	3.09E+06	1.079	9.23	0.0952
1985	Apr	24	18.3	1.51E+04	4.328	6.83	0.4368
1985	Jul	09	17.4	2.36E+06	1.506	7.80	0.1140
1985	Jul	17	17.4	1.83E+06	0.092	4.35	0.1743
1986	Feb	06	13.1	1.16E+07	1.030	10.20	0.1425
1986	Feb	07	13.1	1.05E+06	2.753	8.48	0.1553
1986	Feb	14	13.1	4.70E+05	3.358	8.58	0.1531
2005	Jun	16	28.8	1.19E+08	0.036	4.36	0.0902
2005	Sep	07	25.8	5.95E+06	3.098	5.55	0.3171
2006	Dec	05	12.1	4.18E+07	2.320	8.97	0.1697
sub-sub-GLEs							
1975	Aug	04	14.3	2.99E+06	0.037	4.44	0.0437
[b]1975	Nov	21	16.1	7.94E+03	3.490	n/a	0.0562
1976	Mar	23	12.2	5.00E+04	1.738	2.64	0.7968
1976	Mar	28	12.2	3.83E+06	0.530	7.43	0.0559
[b]1985	Jul	03	17.4	3.61E+06	0.680	*n/a*	0.0490
[c]1985	Jul	20	17.4	8.93E+04	1.490	n/a	n/a
1986	Feb	04	13.1	1.29E+06	0.684	5.33	0.0847
1986	Feb	10	13.1	3.58E+05	1.140	4.70	0.1177
1986	Feb	16	13.1	1.88E+06	1.681	7.37	0.0697
1986	Mar	06	13.0	1.41E+05	2.296	6.54	0.0949
1986	May	04	14.3	3.79E+06	0.714	4.74	0.0945
[c]1985	May	08	14.3	8.27E+03	1.850	n/a	n/a
[b]1987	May	29	26.5	1.62E+06	1.20	n/a	0.0427
[a]1994	Jul	12	28.5	2.67E+07	0.000	n/a	0.0340
1994	Sep	16	26.6	1.59E+05	1.845	6.11	0.0603
1994	Oct	19	28.9	1.01E+05	2.787	5.02	0.1607
1994	Oct	25	28.9	1.53E+07	0.447	7.67	0.0443
[b]1995	Apr	22	20.6	4.02E+03	1.980	n/a	0.1160
1995	Oct	20	12.1	7.13E+06	1.584	6.05	0.0582
[b]1997	Apr	01	16.5	2.97E+04	1.520	n/a	0.0676
1997	Apr	07	16.5	5.91E+04	2.084	5.59	0.0558
1997	May	12	18.3	1.16E+06	1.002	7.86	0.0522
[c]1997	Sep	24	28.3	4.87E+03	1.610	n/a	n/a
2005	May	13	28.9	3.69E+10	0.504	6.15	0.0181
2005	May	14	28.9	1.68E+11	0.303	8.76	0.0191
2005	Jul	13	29.1	2.85E+07	0.790	7.13	0.0404
2005	Jul	14	29.1	5.96E+09	0.013	9.69	0.0374
2005	Jul	17	29.1	1.07E+08	0.496	7.39	0.0500
2005	Jul	25	29.1	4.71E+08	0.815	7.72	0.0464
2005	Aug	22	27.4	1.38E+10	0.078	9.03	0.0350
2005	Sep	01	25.8	1.57E+06	0.290	3.51	0.1499
[a]2005	Sep	13	25.8	1.30E+10	0.000	n/a	0.0329
2006	Jul	06	15.2	1.77E+06	0.896	4.92	0.0771
2006	Dec	14	12.1	2.24E+08	0.120	4.67	0.0674
2010	Aug	14	17.4	3.18E+06	1.053	5.34	0.0619

Alternate functional forms: a=exponential; b=Ellison-Ramaty form; c=power-law

Table A2: Calculated Absorbed Doses for Solar Proton Events during Months with SSN < 30										
			Absorbed Dose (cGy) / Thickness of Aluminum Shielding (g/cm^2)							
Year	Mon	Day	1.1	2	3	4	5	10	20	50
GLEs										
1976	Apr	30	1.21E+01	5.78E+00	3.43E+00	2.35E+00	1.74E+00	6.54E-01	2.12E-01	3.69E-02
2006	Dec	13	6.10E+01	3.21E+01	2.02E+01	1.44E+01	1.10E+01	4.50E+00	1.57E+00	2.88E-01
sub-GLEs										
1974	Nov	5	1.20E+00	5.17E-01	2.84E-01	1.83E-01	1.28E-01	4.00E-02	1.01E-02	1.16E-03
1975	Aug	21	1.50E-01	6.77E-02	3.77E-02	2.43E-02	1.70E-02	5.12E-03	1.19E-03	1.10E-04
1975	Aug	22	4.17E-01	1.96E-01	1.12E-01	7.35E-02	5.20E-02	1.60E-02	3.77E-03	4.76E-04
1976	Aug	22	5.42E-01	2.16E-01	1.10E-01	6.63E-02	4.39E-02	1.10E-02	2.01E-03	1.39E-04
1985	Jan	22	5.98E-01	2.53E-01	1.35E-01	8.39E-02	5.72E-02	1.57E-02	3.23E-03	2.56E-04
1985	Apr	24	2.58E+00	8.50E-01	3.95E-01	2.29E-01	1.50E-01	3.95E-02	9.24E-03	1.20E-03
1985	Jul	9	1.27E+00	5.34E-01	2.85E-01	1.79E-01	1.23E-01	3.54E-02	7.93E-03	7.39E-04
1985	Jul	17	1.54E-01	1.02E-01	7.45E-02	5.88E-02	4.84E-02	2.49E-02	1.10E-02	2.63E-03
1986	Feb	6	4.88E+01	2.43E+01	1.47E+01	1.02E+01	7.62E+00	2.91E+00	9.42E-01	1.24E-02
1986	Feb	7	6.54E+00	2.41E+00	1.19E+00	7.09E-01	4.70E-01	1.25E-01	2.71E-02	2.70E-03
1986	Feb	14	7.36E+00	2.42E+00	1.10E+00	6.23E-01	3.96E-01	9.21E-02	1.74E-02	1.52E-03
2005	Jum	16	3.86E+00	1.97E+00	1.18E+00	7.93E-01	5.68E-01	1.81E-01	5.28E-02	1.00E-02
2005	Sep	7	1.24E+02	4.89E+01	2.57E+01	1.62E+01	1.13E+01	3.61E+00	1.01E+00	1.59E-01
2006	Dec	6	1.46E+02	5.94E+01	3.15E+01	1.98E+01	1.37E+01	4.18E+00	1.06E+00	1.28E-01
sub-sub-GLEs										
1975	Aug	4	8.44E-03	2.98E-03	1.47E-03	8.96E-04	6.09E-04	1.87E-04	5.36E-05	9.98E-06
1975	Nov	21	1.50E-01	6.77E-02	3.77E-02	2.43E-02	1.70E-02	5.12E-03	1.19E-03	1.10E-04
1976	Mar	23	1.44E-01	8.11E-02	5.52E-02	4.22E-02	3.44E-02	1.85E-02	9.85E-03	4.26E-03
1976	Mar	28	6.90E-02	2.35E-02	1.03E-02	5.54E-03	3.29E-03	5.75E-04	8.72E-05	8.11E-06
1985	Jul	3	4.81E-02	1.43E-02	5.65E-03	2.79E-03	1.55E-03	2.10E-04	1.89E-05	1.49E-06
1985	Jul	20	2.14E-01	1.28E-01	9.08E-02	7.16E-02	5.97E-02	3.47E-02	2.01E-02	9.64E-03
1986	Feb	4	1.02E-01	4.41E-02	2.36E-02	1.47E-02	9.95E-03	2.65E-03	6.21E-04	8.90E-05
1986	Feb	10	1.13E-01	5.16E-02	2.92E-02	1.91E-02	1.35E-02	4.23E-03	1.14E-03	1.96E-04
1986	Feb	16	4.24E-01	1.36E-01	5.85E-02	3.11E-02	1.86E-02	3.32E-03	5.13E-04	4.86E-05
1986	Mar	6	1.83E-01	6.17E-02	2.80E-02	1.57E-02	9.76E-03	2.06E-03	3.74E-04	4.04E-05
1986	May	4	4.01E-01	1.82E-01	1.01E-01	6.46E-02	4.48E-02	1.32E-02	3.52E-03	5.97E-04
1986	May	8	3.82E-02	2.14E-02	1.45E-02	1.11E-02	8.98E-03	4.79E-03	2.54E-03	1.09E-03
1987	May	29	1.95E-02	4.96E-03	1.80E-03	8.46E-04	4.56E-04	5.82E-05	5.59E-06	5.64E-07
1994	Jul	12	1.81E-02	4.07E-03	1.29E-03	5.28E-04	2.51E-04	2.00E-05	1.73E-06	3.99E-07
1994	Sep	16	2.85E-02	7.91E-03	3.19E-03	1.69E-03	1.03E-03	2.26E-04	4.54E-05	5.52E-06
1994	Oct	19	6.90E-01	2.54E-01	1.25E-01	7.47E-02	4.94E-02	1.35E-02	3.40E-03	5.36E-04
1994	Oct	25	9.05E-02	2.53E-02	9.48E-03	4.47E-03	2.46E-03	3.97E-04	5.92E-05	5.90E-06
1995	Apr	22	4.73E-03	1.83E-03	9.25E-04	5.60E-04	3.73E-04	9.81E-05	2.01E-05	1.73E-06
1995	Oct	20	7.55E-01	2.14E-01	8.70E-02	4.62E-02	2.82E-02	6.27E-03	1.28E-03	1.57E-04
1997	Apr	1	4.75E-03	1.54E-03	6.66E-04	3.55E-04	2.13E-04	3.77E-05	4.65E-06	2.72E-07
1997	Apr	7	1.15E-02	3.31E-03	1.42E-03	7.83E-04	4.94E-04	1.20E-04	2.70E-05	3.69E-06
1997	May	12	3.29E-02	9.68E-03	3.84E-03	1.90E-03	1.05E-03	1.64E-04	2.34E-05	2.24E-06
1997	Sep	24	1.46E-02	8.52E-03	5.96E-03	4.65E-03	3.84E-03	2.17E-03	1.22E-03	5.63E-04
2005	May	13	1.56E+00	4.08E-01	1.64E-01	8.63E-02	5.24E-02	1.14E-02	2.30E-03	2.82E-04
2005	May	14	1.78E+00	2.98E-01	8.80E-02	3.73E-02	1.92E-02	2.72E-03	4.65E-04	7.77E-05
2005	Jul	13	1.75E-01	4.13E-02	1.48E-02	7.17E-03	4.08E-03	7.37E-04	1.23E-04	1.33E-05
2005	Jul	14	8.37E+00	2.09E+00	6.94E-01	2.90E-01	1.40E-01	1.54E-02	1.78E-03	2.29E-04
2005	Jul	17	1.17E+00	3.65E-01	1.50E-01	7.54E-02	4.25E-02	7.24E-03	1.12E-03	1.09E-04
2005	Jul	25	6.04E+00	1.65E+00	6.13E-01	2.87E-01	1.58E-01	2.52E-02	3.74E-03	3.76E-04
2005	Aug	22	1.26E+01	2.91E+00	9.25E-01	3.85E-01	1.93E-01	2.44E-02	3.15E-03	3.93E-04
2005	Sep	1	1.60E-01	9.91E-02	6.87E-02	5.18E-02	4.10E-02	1.79E-02	6.44E-03	1.59E-03
2005	Sep	13	6.98E+00	1.43E+00	4.13E-01	1.65E-01	8.07E-02	9.48E-03	1.26E-03	1.88E-04
2006	Jul	6	1.55E-01	6.07E-02	2.99E-02	1.75E-02	1.15E-02	3.20E-03	8.23E-04	1.33E-04
2006	Dec	14	3.93E+00	1.64E+00	8.35E-01	4.98E-01	3.33E-01	9.76E-02	2.65E-02	4.61E-03
2010	Aug	14	1.84E-01	5.98E-02	2.65E-02	1.49E-02	9.56E-03	2.45E-03	5.76E-04	8.33E-05