Probability Estimates of Solar Particle Event Doses During a Period of Low Sunspot Number for Thinly-Shielded Spacecraft and Short Duration Missions

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In an earlier paper (Atwell, et al., 2015), we investigated solar particle event (SPE) radiation exposures (absorbed dose) to small, thinly-shielded spacecraft during a period when the sunspot number (SSN) was less than 30. These SPEs contain Ground Level Events (GLE), sub-GLEs, and sub-sub-GLEs (Tylka and Dietrich, 2009, Tylka and Dietrich, 2008, and Atwell, et al., 2008). GLEs are extremely energetic solar particle events having proton energies extending into the several GeV range and producing secondary particles in the atmosphere, mostly neutrons, observed with ground station neutron monitors. Sub-GLE events are less energetic, extending into the several hundred MeV range, but do not produce secondary atmospheric particles. 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. In this paper, we consider those SPEs that occurred during 1973-2010 when the SSN was greater than 30 but less than 50. In addition, we provide probability estimates of absorbed dose based on mission duration with a 95% confidence level (CL). We also discuss the implications of these data and provide some recommendations that may be useful to spacecraft designers of these smaller spacecraft.

Nomenclature

Al = chemical symbol for aluminum
cGy = absorbed dose unit centiGray
CL = confidence level
GCR = galactic cosmic ray
GeV = unit of energy Giga-electron volt
GLE = ground level event (or enhancement)
HDPE = high density polyethylene
HZETRN = NASA Langley Research Center-developed high energy particle transport/dose code
MeV = unit of energy Mega-electron volt
SEP = solar energetic particle
SPE = solar particle event
SSN = smoothed sunspot number
TID = total ionizing dose

I. 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 (Atwell, et al., 2015), we began the process of developing a new method for radiation analysis by investigating the quiet solar environment with sunspot numbers less than 30 in the historical record. 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 consider a probabilistic assessment of receiving a given dose based on mission duration with a 95% confidence level.

II. Background

The two most prevalent sources of primary radiation in deep space are galactic cosmic rays (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 following figure (Figure 1) that shows the sunspot numbers for each of the solar cycles in the manned space era.

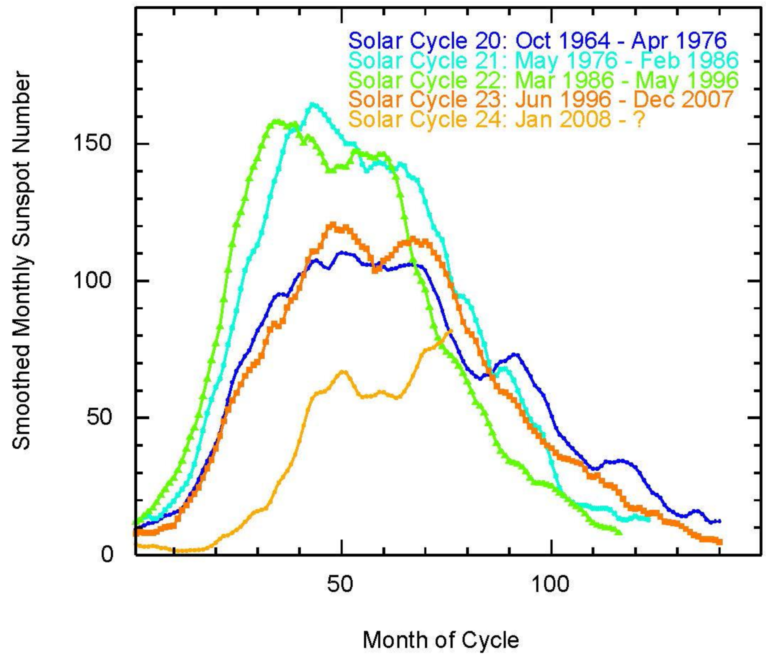


Figure 1: Smoothed sunspot numbers in the manned space era (since 1964) plotted versus the month of the cycle (for solar cycles 20-24) (Atwell, et al., 2015).

III. Data Sources and Methodology

Forty solar particle events occurred during 1973-2011 with a sun spot number between 30 and 50. Of these events, six were denoted as ground level events, which are extremely energetic SPEs having proton energies extending into the several GeV range 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 are less energetic and extend into the several hundred MeV range, but do not produce secondary atmospheric particles. The remaining 27 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 shows the four Band fit parameters (reference to Band fitting) for each event. For detailed information on how we extracted the Band fit for each of the events, refer to section III in our previous paper (Atwell, et al., 2015).

Table 1: Band fit parameters for the solar particle events (notional numbers that need to be reviewed). (Note: still need the data on the highlighted parameters from Allan)

Yr	Mo	Day	J_o (p/cm^2)	γ1	γ2	R_o (GV)
GLEs						
1973	Apr	29	7.24E+06	1.073	4.440	0.1628
1977	Sep	19	1.39E+06	2.995	7.950	0.3163
1977	Sep	24	4.32E+06	1.730	5.400	0.3390
1997	Nov	06	8.15E+08	0.284	5.380	0.1159
2005	Jan	17	3.51E+07	2.649	8.290	0.1619
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]						
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1974	Sep	24	9.06E+06	0.780	4.920	0.1817
1984	Apr	25	4.53E+09	0.513	6.070	0.0582
1997	Nov	04	5.44E+06	1.354	9.170	0.1567
2004	Nov	01	1.44E+09	-0.906	6.170	0.0538

Notional Numbers

2004	Nov	10	2.41E+08	1.130	5.990	0.0647
sub-sub-GLEs						
1973	Nov	03	1.99E+06	1.238	3.440	0.0820
1974	Jul	3	1.40E+07	1.906	7.830	0.0448
1974	Jul	5	1.72E+10	0.403	9.040	0.0287
1974	Sep	11	1.10E+11	-0.756	[illegible]	[illegible]
1974	Sep	20	1.34E+09	0.766	[illegible]	[illegible]
1977	Sep	08	5.09E+07	[illegible]	[illegible]	[illegible]
1977	Sep	17	4.25E+07	[illegible]	[illegible]	[illegible]
1977	Oct	12	6.87E+05	[illegible]	[illegible]	0.0789
1984	May	21				
1984	May	23				
1984	Jun	01	[illegible]	[illegible]	4.900	0.2007
1987	Nov	07	[illegible]	[illegible]	5.190	0.0099
1994	Feb	[illegible]	[illegible]	-0.078	4.850	0.0359
1994	Feb	[illegible]				
2004	[illegible]	[illegible]	[illegible]	0.644	6.850	0.0326
2004	[illegible]	[illegible]	[illegible]	3.298	5.740	0.1602
[illegible]	[illegible]	[illegible]	2.04E+09	0.710	8.980	0.0344
[illegible]	[illegible]	[illegible]	1.76E+13	-1.881	4.020	0.0088
2004	[illegible]	13				
2004	[illegible]	19	1.38E+08	0.374	6.120	0.0533
2004	[illegible]	07	1.90E+09	0.787	7.390	0.0372
2004	Dec	3	1.38E+05	2.027	5.510	0.0782
2005	Jan	15	5.67E+05	1.584	4.290	0.0966
2005	Jan	16	1.76E+09	0.505	7.880	0.0490
2011	Jan	28	2.20E+04	2.217	4.250	0.1883
2011	Mar	07	1.59E+09	0.200	6.560	0.0358
2011	Mar	21	1.35E+07	0.676	4.890	0.0746

For reference, we show a few plots of the events in the table above: two each for the GLEs (Figure 2), two each for the sub-GLEs (Figure 3), and two each for the sub-sub-GLEs (Figure 4). The four band fit parameters are shown within each plot, and in general, these fits are valid only for proton energies greater than 10 MeV. Also, note that a few of the Band fits have the lower-rigidity power-law index $\gamma_1 < 0$. Since the integral proton spectrum must be a strictly non-increasing function of rigidity, this parameter value would give unphysical results if extrapolated to very low rigidities. Nevertheless, these $\gamma_1 < 0$ values, combined with the exponential rollover, serve to provide good empirical descriptions for the proton spectrum at energies relevant for space-system design.

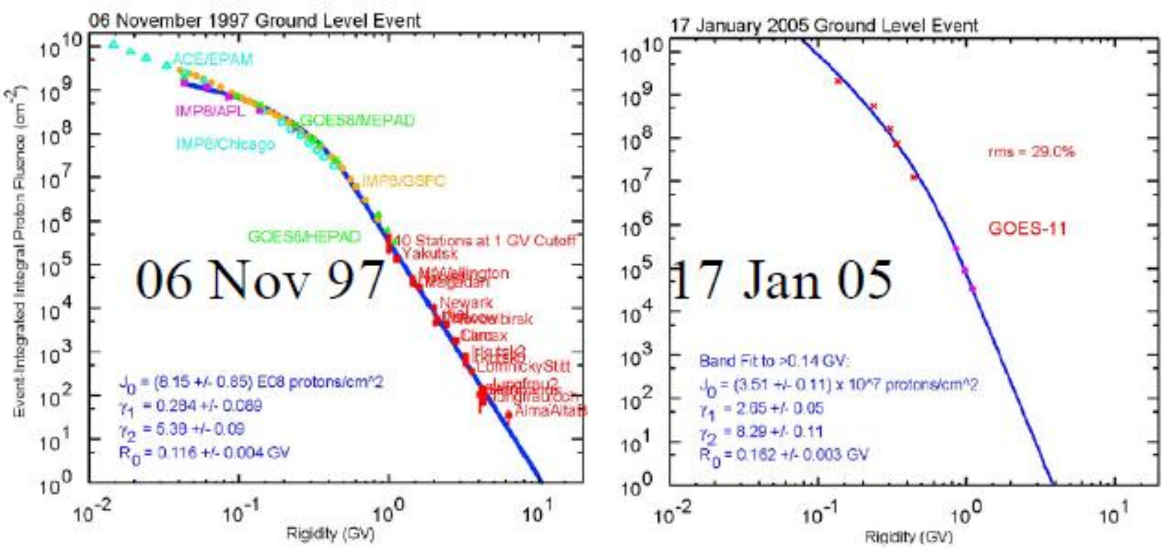


Figure 2: Band function fits to GLEs. Note that data points less than 0.13 GV (less than 10 MeV) are not included in the fits. (Update any Band fit parameters as necessary)

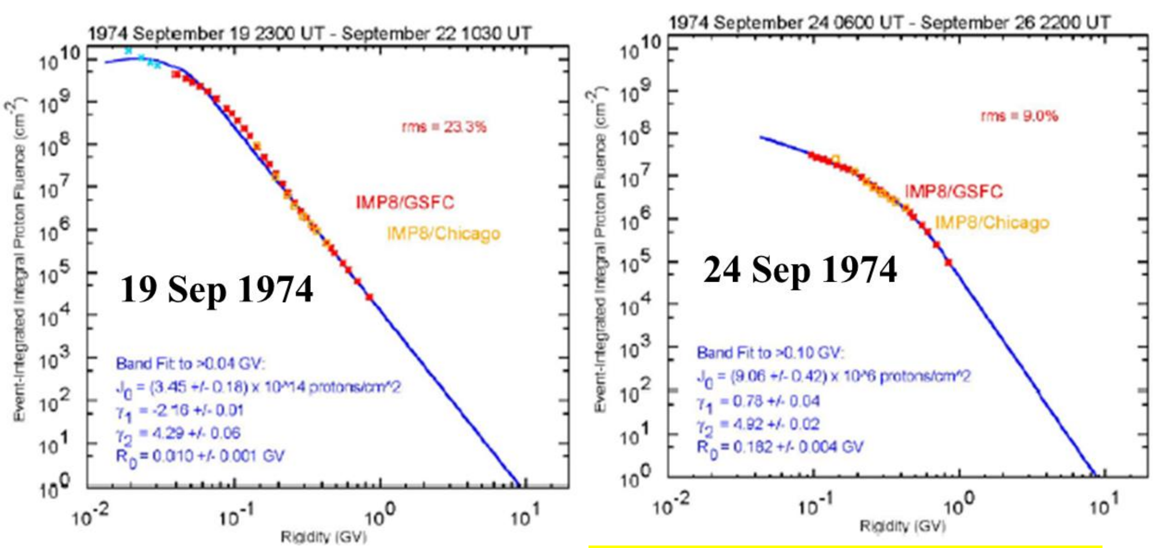
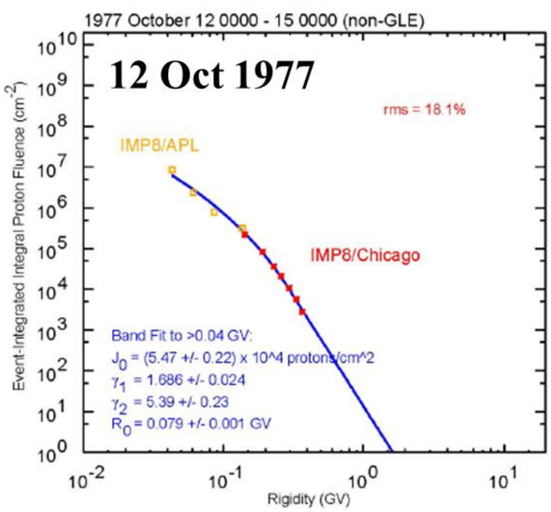


Figure 3: Band function fits to sub-GLEs. (Update any Band fit parameters as necessary)



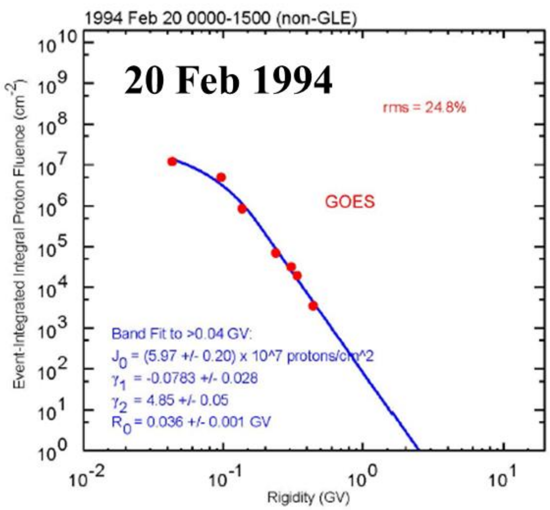


Figure 4: Band function fits to sub-sub-GLEs. (Need to update these plots to have the corrected J_0 parameter) (Update any Band fit parameters as necessary)

The differential fluence of these Band fits were created and formatted to make the dose computations with HZETRN 2005, a high-energy particle transport/dose code developed at Langley Research Center (Townsend and Tripathi, 1995). 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 2, 5, 10, 20, and 50 g/cm^2. 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.

IV. Results

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.

Table 2: Absorbed dose (cGy in Si) in various thicknesses of aluminum for SPEs during SSNs between 30-50. Doses highlighted in green are the highest doses for the given thickness.

Date	Event Type	2 (g/cm^2)	5 (g/cm^2)	10 (g/cm^2)	20 (g/cm^2)	50 (g/cm^2)
1973 Apr 29	GLE	1.247	0.4123	0.1594	0.0529	0.0099
1977 Sep 19	GLE	7.466	1.8	0.578	0.1712	0.028
1977 Sep 24	GLE	3.956	1.399	0.6075	0.2461	0.0619
1997 Nov 06	GLE	25.47	8.665	3.263	1.005	0.1454
2005 Jan 17	GLE	55.87	11.67	3.172	0.7457	0.0803
2005 Jan 20	GLE	50.82	20.84	9.763	4.091	0.9753
1973 Nov 02	sub-GLE	0.1107	0.0261	0.0075	0.0018	0.0002
1974 Sep 19	sub-GLE	0.9143	0.1978	0.0615	0.0188	0.0037
1974 Sep 24	sub-GLE	1.168	0.4464	0.1956	0.0755	0.0156
1984 Apr 25	sub-GLE	23.24	3.614	0.775	0.1623	0.02
1997 Nov 04	sub-GLE	1.332	0.3971	0.1414	0.0434	0.0064
2004 Nov 01	sub-GLE	0.7769	0.1571	0.0337	0.0069	0.0008
2004 Nov 10	sub-GLE	4.652	0.6817	0.1487	0.0318	0.004

1973 Nov 03	sub-sub	0.142	0.038	0.014	0.005	0.001
1974 July 03	sub-sub	0.171	0.014	0.00222	0.00034	0.00004
1974 July 05	sub-sub	1.089	0.0648	0.0084	0.0013	0.0002
1974 Sept 11	sub-sub	2.685	0.179	0.024	0.003	0.00038
1974 Sept 20	sub-sub	0.0721	0.0108	0.0027	0.0006	0.0001
1977 Sept 08	sub-sub	0.1319	0.0167	0.0036	0.0007	0.0001
1977 Sept 17	sub-sub	0.5471	0.1006	0.0286	0.0075	0.0013
1977 Oct 12	sub-sub	0.006	0.001	0.00024	0.00006	0.00001
1984 June 01	sub-sub	0.0065	0.0012	0.0003	0.0001	0.00001
1987 Nov 07	sub-sub	0.1189	0.0198	0.0052	0.0013	0.0002
1994 Feb 20	sub-sub	0.017	0.003	0.0009	0.0002	0.00004
1994 Apr 11	sub-sub	0.121	0.01282	0.00245	0.00044	0.000049
2004 July 22	sub-sub	0.031	0.00768	0.00248	0.00074	0.00015
2004 July 25	sub-sub	0.873	0.054	0.00692	0.00096	0.00013
2004 July 30	sub-sub	0.08	0.01831	0.00613	0.00194	0.00041
2004 Sept 19	sub-sub	0.543	0.075	0.01636	0.00327	0.00039
2004 Nov 07	sub-sub	0.127	0.012	0.002	0.0003	0.00004
2004 Dec 03	sub-sub	0.023	0.00355	0.00088	0.0002	0.000028
2005 Jan 15	sub-sub	0.094	0.01998	0.00632	0.00187	0.00036
2005 Jan 16	sub-sub	5.479	0.618	0.096	0.0136	0.0013
2011 Jan 28	sub-sub	0.031	0.00768	0.00248	0.00074	0.00015
2011 Mar 07	sub-sub	0.479	0.055	0.0111	0.00205	0.00023
2011 Mar 21	sub-sub	0.308	0.06	0.0167	0.0043	0.0007

V. Discussion

In general, we find the highest doses are produced by GLE events. Therefore, for the case where sunspots are in the 30-50 range, 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 April 25) that produces more dose than some of the GLEs (1977 Sep 24, 1977 Sep 19, and 1973 Apr 29). In Figure 5, the April 25 1984 sub-GLE has a higher fluence over the September 24 1977 and September 19 1977 GLE until approximately 150 MeV and a higher fluence over the April 29 1973 GLE until approximately 600 MeV.

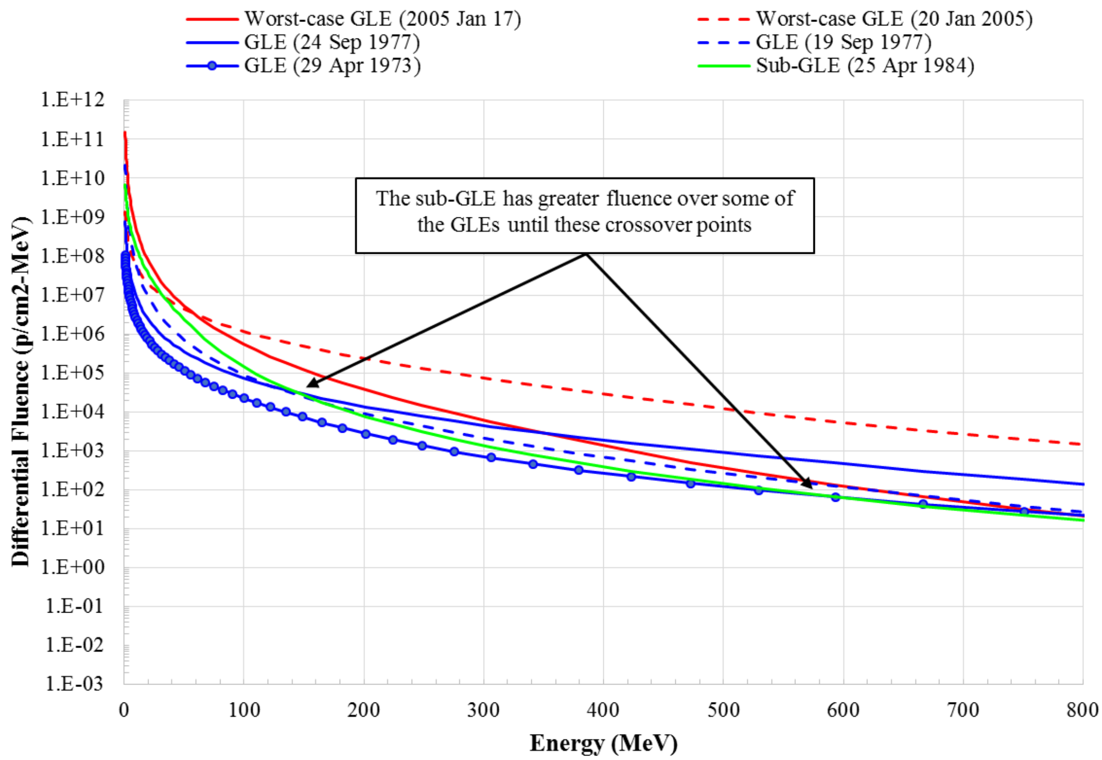


Figure 5: Comparison of several GLEs to a sub-GLE that has greater differential fluence over certain parts of the spectrum.

There are even some sub-sub-GLEs (2005 Jan 16 and 1974 Sep 11) that produce higher doses than some of the GLEs (1973 Apr 29 and 1977 Sep 24). In Figure 6, the two sub-sub-GLEs have a higher differential fluence over the September 24 1977 GLE until approximately 43 MeV and a higher fluence over the April 29 1973 GLE until 60 MeV (September 11 1974) and 83 MeV (January 16 2005). These higher fluences correlate to the dose results shown in Table 2. Thus, the smaller intensity events cannot be completely discounted and should be included as part of the overall assessment.

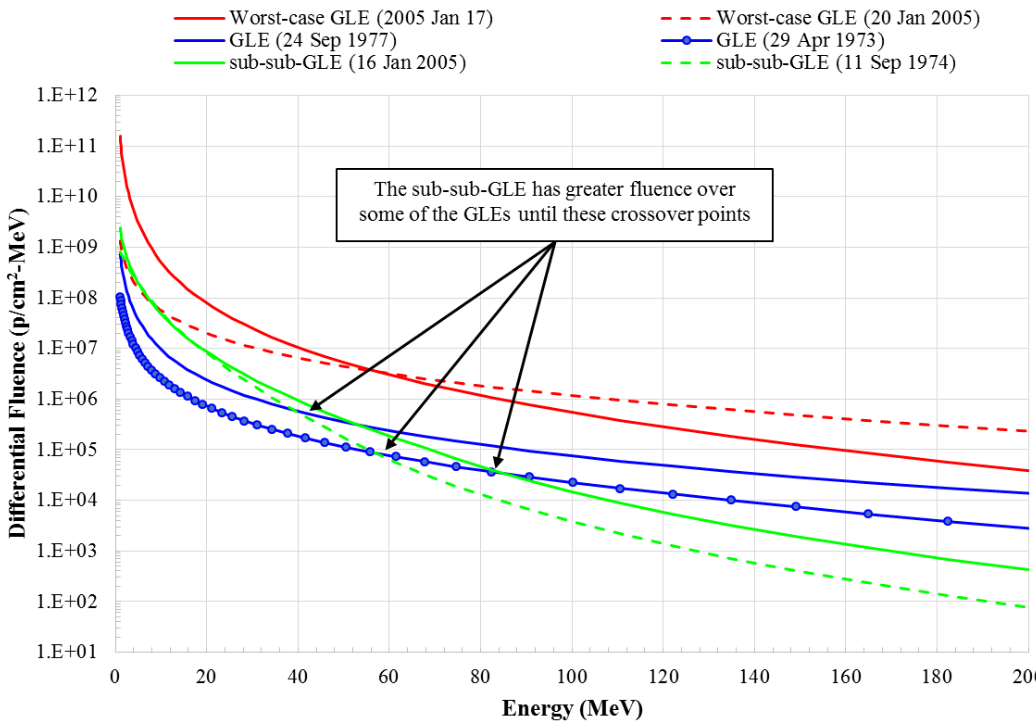


Figure 6: Comparison of several GLEs to sub-sub-GLEs that have greater differential fluence over certain parts of the spectrum.

When we compare this data set with our previous paper, we see that there are more GLEs in the data with SSN between 30 and 50 (six events) than the data with SSN less than 30 (two events). The doses between the two data sets are comparable. However, in the GLEs with SSN between 30 and 50 we have some events that produce significantly more dose. Given that higher sunspot number generally correlates with greater solar activity and intensity of events, our data tends to match that correlation.

As was mentioned in the introduction, the standard method of TID estimation for missions has been to use the historical worst case SPE for all-time to determine the potential worst-case dose exposure to the vehicle. This worst case GLE is typically the October 1989 series of events. Comparing the doses for this worst case GLE (10-1989) to the worst case GLEs for SSNs between 30 and 50 (Table 3), we see that using the 10-1989 GLE for this analysis would greatly overestimate the dose exposure to a vehicle whose mission happens to be during relative solar quiet conditions. This would in turn lead to overdesign of the shielding for the vehicle, increasing the mass and potential cost to the mission.

Table 3: Comparison of the worst case GLEs for SSNs between 30 and 50 with the all-time historical worst case SPE. The percent increase in dose is calculated from the highlighted cell, representing the worst-case dose at a given thickness for a mission during relative solar quiet conditions (SSN between 30 and 50).

Date	Event Type	2 (g/cm^2)	5 (g/cm^2)	10 (g/cm^2)	20 (g/cm^2)	50 (g/cm^2)
2005 Jan 17	GLE	55.87	11.67	3.172	0.7457	0.0803
2005 Jan 20	GLE	50.82	20.84	9.763	4.091	0.9753
1989 Oct 19-24	GLE	914.5	239.9	85.89	28.28	5.19
% Increase		1537%	1877%	2400%	3244%	5249%

- Need to develop details on the probabilistic assessment of receiving a given dose due to the SPEs and the implications to designers

VI. Summary and Conclusions

References

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Reference to Band fit