HIGH-ENERGY SEP MODELLING FOR LARGE SOLAR PARTICLE EVENTS

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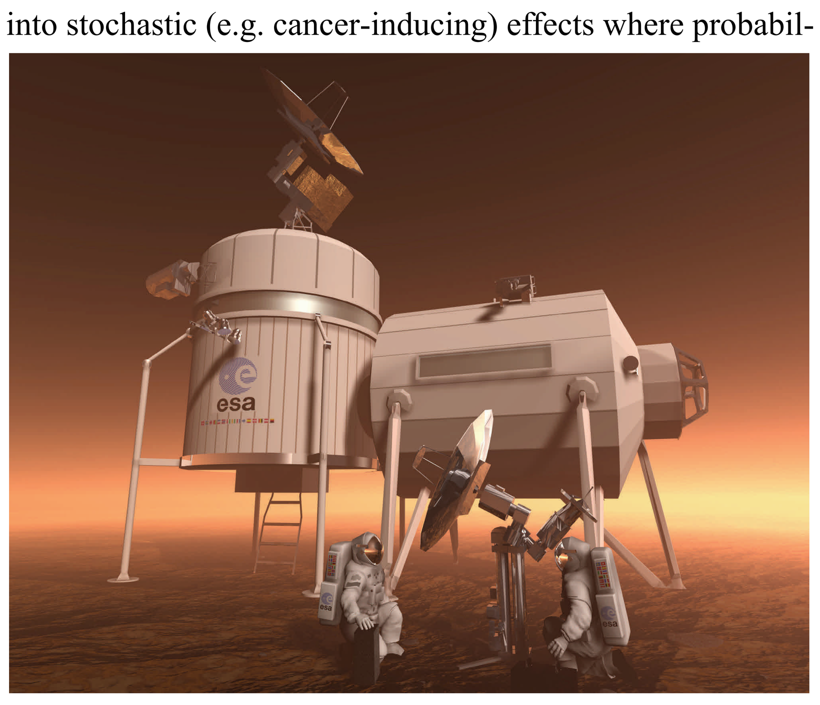
ABSTRACT 1

Predicting the radiation environment is critical for any space mission and one important source of radiation is the Sun. In the specification of the solar energetic particle (SEP) environment, previous work on the ESA SEPEM System has focussed on the 5 - 200 MeV range (Jiggens et al., 2012) as this is critical for electronics components behind nominal spacecraft shielding. It is also well measured by a variety of space-borne instrumentation. However, for human spaceflight the shielding levels are far greater and therefore the critical energy of incident particles is also higher. Unfortunately, the high energy solar proton measurements come with a great deal of uncertainty as a result of the width of the energy bins of monitors meaning that the correct average energy of particles is difficult to discern and, furthermore, there are fewer instruments taking measurements in this range thus reducing the length of the high-energy solar proton dataset and the ability to calibrate measurements. The most important source of data for overcoming these dataset limitations is the data from neutron monitors (NMs) which see flux enhancements as a result of the secondary neutrons produced when high energy solar protons are attenuated in the upper atmosphere. By first subtracting the contribution from galactic cosmic rays (GCRs) and then accounting for the particle cut-off rigidity based on the location of the NMs SEP event proton fluences at very high-energies can be discerned. Work done by Tylka and Dietrich (2009) provides a reliable starting point by describing the combined satellite and neutron-monitor event-integrated proton spectra with a Band function (Band et al., 1993). Using this data, we present probabilistic models for the high energy proton environment for use in spacecraft missions where solar particles from 200 MeV to 1 GeV and beyond are important. The work, focussing on solar protons, is supported by ESA's General Studies Programme. Solar heavy ions are also important especially for single event effects in components and doses in humans and this is investigated under a separate activity named ESHIEM funded through ESA's Technology Research Programme.

HUMAN EFFECTS OF SPACE RADIATION 2

The space radiation environment presents important challenges to crew health and safety for long-duration missions. Interplanetary missions to the Moon, Mars or near Earth asteroids carry additional risks from being beyond the shielding provided by the geomagnetic field that helps protect International Space Station (ISS) missions in low-Earth orbit, and also the opportunity for rapid return of crews to Earth in the event of emergencies. These together with the long duration of missions from several months to approximately three years, which are needed for travel beyond the Earth-Moon system, significantly increases the risk of harm to crew health.

Effects of radiation on humans in space are divided into stochastic (e.g. cancer-inducing) effects where probability is a function of dose and tissue reactions (e.g. eye cataracts) which will 'definitely' occur beyond a threshold dose.



The contribution of Solar Particle Events (SPEs) towards doses in humans on EVA is understood to be unacceptable necessitating the existence of a warning system for human deep space missions. However, the contribution of such events for astronauts inside a spacecraft behind substantial shielding is less clear. This is due, in part, to the uncertainty of the high energy portion of the SPE spectrum (> 200 MeV) which becomes dominant for such scenarios. A proton energy of >175 MeV is needed to penetrate 10 cm of Aluminium shielding.

WORST-CASE EVENT FLUENCE RESULTS 4

For the development of a worst-case peak flux environment for human exploration neutron monitor data was no longer suitable as the time resolution at which it could be extrapolated to relevant energies was too low. Therefore, data from GOES/HEPAD detector was combined with that from the SEPEM database for 2 'worst-cases': September 1989 (for solar maximum) and December 2006 (for solar minimum). The solar minimum case is important as the GCR environment during solar minimum is enhanced due to reduced attenuation from the solar wind. Combining the worst-case solar maximum event with the GCR environment at solar minimum would exaggerate the risk to astronauts.

In order to produce a coherent spectrum, including the HEPAD data, a fit was made for each of the two SPEs. The best fit for peak fluxes in the case of the September 1989 SPE was found to be a 2nd order polynomial as a function of Energy in the logarithmic domain. In the case of the December 2006 SPE the best fit was a simple power law as a function of Energy.

Figure 4 shows the data from these two SPEs and the fits compared with the 90% and 95% modelled peak fluxes using the SEPEM virtual timelines method for a duration of 3 years at solar maximum conditions extrapolated with a power law to high energies. Firstly, it is clear that these SPEs are not the worst case for low energies. However, at high energies they exceed the model. This demonstrates that, while the model is reasonable up to 200 MeV (the September 1989 SPE being a good match at 200 MeV), an extrapoltion of the model is not appropriate for human spaceflight and therefore more data must be used.

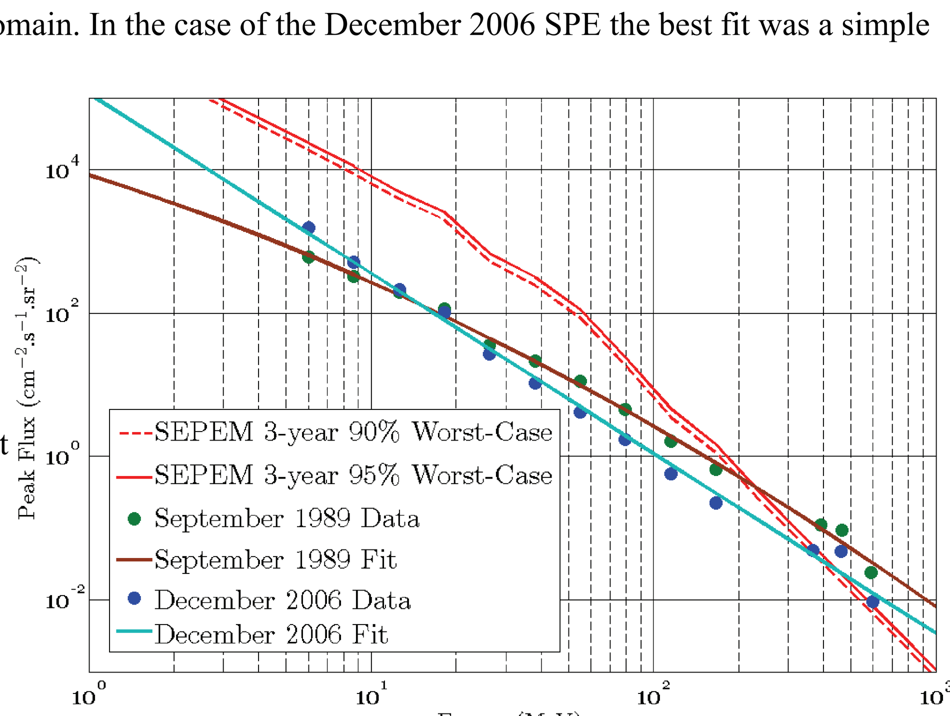


Figure 4: Comparison of 3-year Mission peak flux results against observed 'worst-cases' of September 1989 and December 2006

EXTENDING THE MISSION FLUENCE ENERGY RANGE 3

In order to extend the energy range of the existing Solar Energetic Particle (SEP) environment model (see Jiggens et al. 2012), a new data set produced using neutron monitor data was used (see Tylka and Dietrich, 2009). This allows for the necessary extension of proton energy range up to >1 GeV.

Based on the neutron monitor data set, Figure 1 shows the mission fluence against the probability of it being exceeded (one minus the confidence level) for protons in the range 450 to 675 MeV for a range of mission durations. Each of these models is for solar maximum only with the exception of that for 11 years which also incorporates 4 years of solar minimum to achieve a fluence for a complete solar cycle.

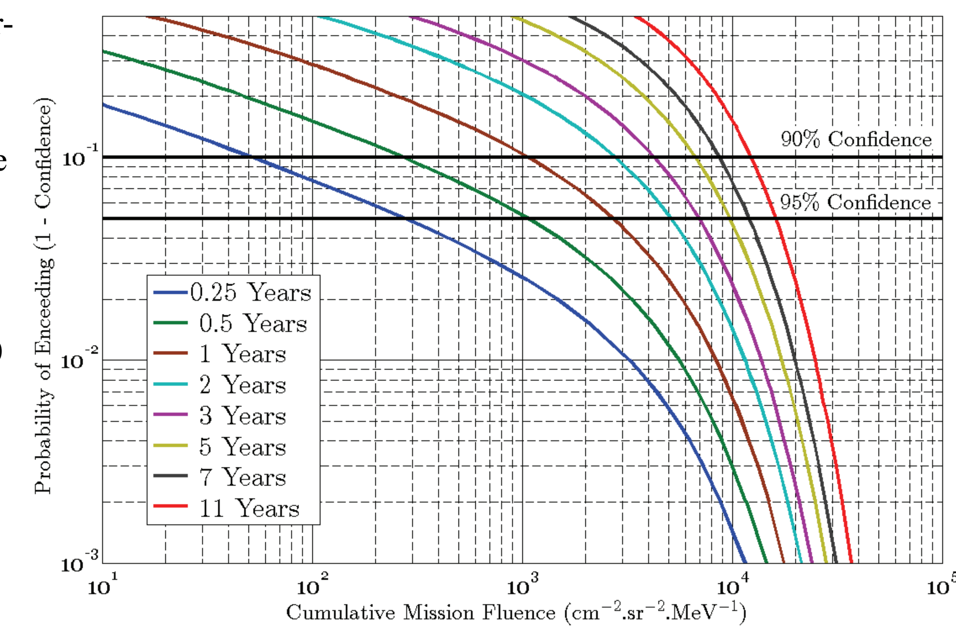


Figure 1: Cumulative Mission Fluence against confidence for protons in the 450.0-675.0 MeV range based on NM data.

Table 1 shows the differential energy channels used for this work. These incorporate the 10 energy bins of the SEPEM reference proton dataset and 4 additional high energy channels to extend the upper limit of the energy range from 200 MeV to 1 GeV. In the last column the weighting factor given to the neutron monitor results against the original SEPEM results is shown. A channel of > 1 GeV was also available from the NM data.

Table 1: Table of Energy Channels

Ch.	E_L (MeV)	E_U (MeV)	E_C (MeV)	w
P1	5.00	7.23	6.01	0.0
P2	7.23	10.46	8.69	0.0
P3	10.46	15.12	12.6	0.0
P4	15.12	21.87	18.2	0.0
P5	21.87	31.62	26.3	0.0
P6	31.62	45.73	38.0	0.0
P7	45.73	66.13	55.0	0.125
P8	66.13	95.64	79.5	0.375
P9	95.64	138.3	115.0	0.625
P10	138.3	200.0	166.3	0.875
P11	200.0	300.0	244.9	1.0
P12	300.0	450.0	367.4	1.0
P13	450.0	675.0	551.1	1.0
P14	675.0	1012.5	826.7	1.0

Table 2: Fluence change (%) cause by increasing free parameters in exp. cut-off power law from 2 to 3.

Energy (MeV)	1 year	3 years	7 years
12.58	-24.9	-16.9	-16.9
18.18	-28.7	-18.0	-17.2
26.3	-28.2	-18.9	-19.1
38.03	-25.0	-17.7	-15.8
54.99	-16.4	-12.5	-11.8
79.53	-6.9	-5.6	-6.1
115.01	-0.2	0.3	-0.2
166.31	2.3	1.4	1.9
244.95	-9.6	-6.7	-5.8
367.42	-21.6	-11.3	-9.4
551.14	-34.0	-18.7	-10.1
826.7	-43.2	-24.7	-12.5

For the neutron monitor event list, comprising of 43 SPEs, the distribution used for the SPE waiting times was a Poisson distribution. As these large events are less frequent and can therefore be considered approximately random in time, the use of the Lévy distribution (see Jiggens & Gabriel, 2009) used for the SEPEM data of 250 events was not justified.

Power laws were previously proposed for event fluence distributions by Gabriel & Feynman (1996), Xapsos (1999) and Nymmik (e.g. 2011) while Feynman et al. 1993 applying a lognormal distribution. Critically, all distributions previously used provide reasonable fits to the high energy data. However, the 2-free parameter power law with exponential cut-off (Nymmik, 2011) used in the SEPEM model was not a perfect fit at all energies. Due to the limited number of events, introducing a cut-off for significant events thereby reducing the points for the fit was not desirable. However, SPEs do have very different spectra and are important at different energy ranges. The impact of adding a 3rd free parameter, allowing the minimum fluence to vary, is illustrated in Figure 2. This provides improved fits to the data especially for channels P3 to P6 (disregarded in the final model result - see Table 1) and P12 to P14. In almost all cases the introduction of a third free parameter reduces the fluence, as shown in Table 2, making the results less conservative, this is more pronounced for lower mission durations. For this reason and for statistical parsimony (desire to use the fewest free parameters) the 2-parameter distribution was kept in this analysis.

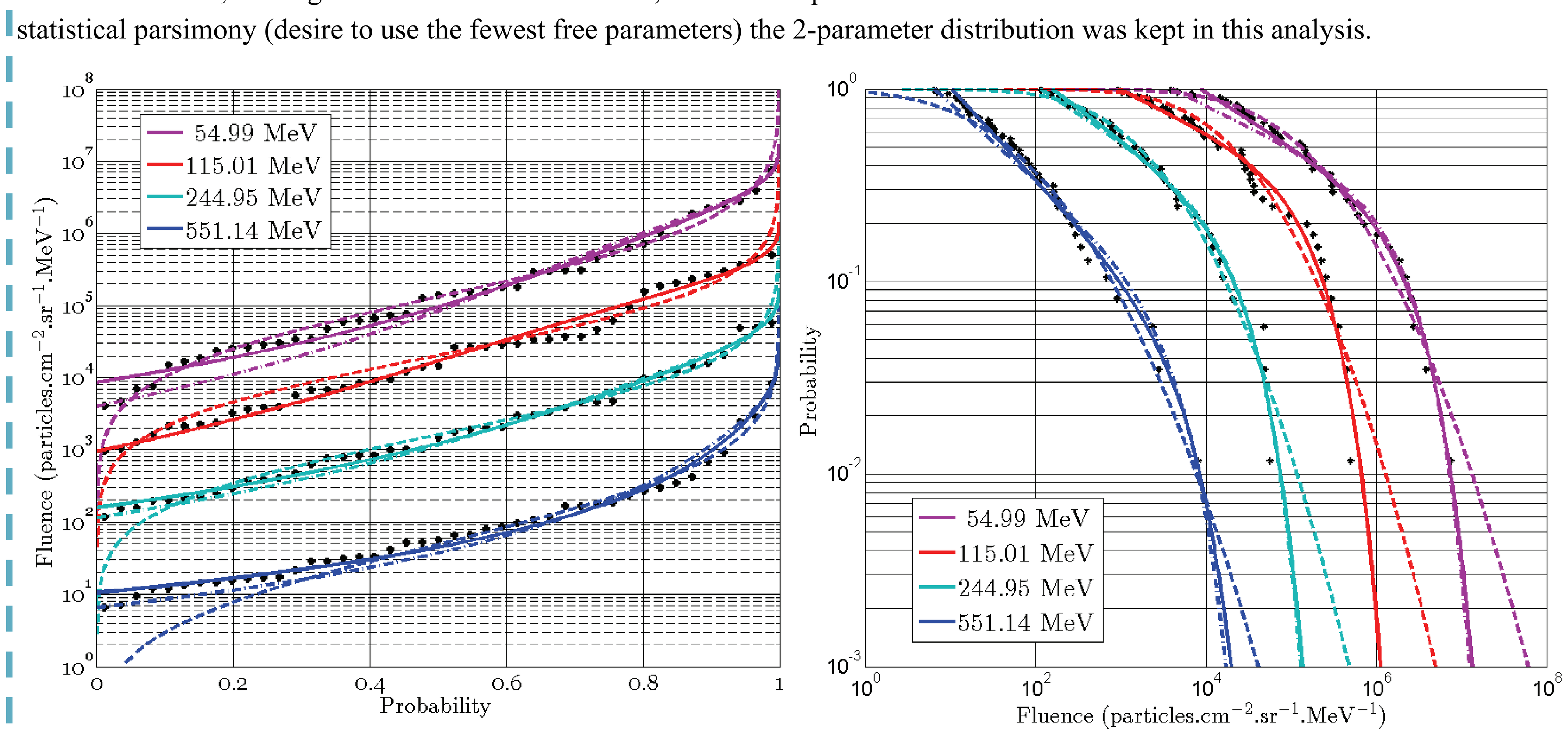


Figure 2: Lognormal (dashed), 2-parameter (dash-dotted) and 3-parameter (solid) power law with exponential cut-off distribution fits for SPEs based on neutron monitor data in 4 energy bins.

The final result for a 3-year mission in the differential (binned) channels is shown in Figure 3. The original SEPEM result is shown (blue dots) alongside the neutron monitor result (green dots). Given the differences in the datasets, in terms of both the time range of SPEs included and the methods of processing the data, the agreement of results at energies below 100 MeV is exceptionally good.

The red line shows a Band fit (Band et al. 1993), usually applied to the SPE fluence, now applied to the SEPEM cumulative fluence result to extrapolate to high energies. The turquoise line shows the new result combining the space-based data and NM data using weighting factors given in Table 1.

The results for a 3-year mission are shown as it is a reasonable duration for a human return mission to Mars. However, similar agreement is found for other durations albeit with NM results comparably reduced for shorter durations as the smaller events become more significant.

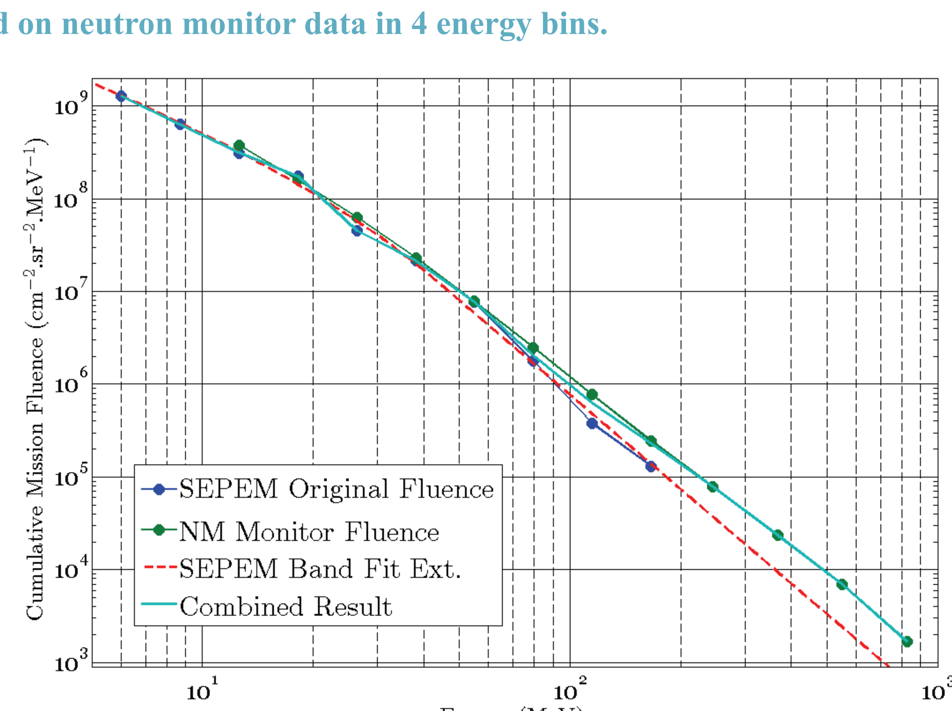


Figure 3: Comparison of 3-year Mission Cumulative fluence results in separate differential channels at 95% confidence.

CONCLUSIONS AND IMPLICATIONS 5

We have presented preliminary results on the extension of the existing 'SEPEM Virtual Timelines' model (Jiggens et al., 2012) using neutron monitor data. Results based solely upon neutron monitor data compare exceptionally well with the existing model for energies between 10 MeV and 75 MeV. Below the 10 MeV level the events not detected by neutron monitors are significant to the total mission fluence contribution and the extrapolation introduces significant errors. In the 10 to 75 MeV range the large events detected by neutron monitors are already dominant for high confidence level calculations and therefore the agreement should be strong. Above 75 MeV the SPE list from space-based data becomes sparse in energy resolution and short in terms of significant SPEs. The addition of the neutron monitor data to the model therefore has a profound impact on the results for high energies (> 100 MeV). With a longer time series of neutron monitor data, more reliable fluence distributions can be constructed mitigating the great problem of lack of data for SPEs at high energies. Due to the existence of some very large events in the NM data set (such as that of February 1956) the mission fluences are increased. Figure 5 shows the integrated 3-year mission fluence values for the expanded model and Band function fits to the existing SEPEM Virtual Timelines models and to the newly extended model using NM data. Table 3 shows results for 1, 3 and 5 years for selected energies.

These results provide a greater certainty for use in dose estimations in humans behind realistic shielding geometries. The approximate doubling of the fluences at > 200 MeV and up to ×4 at > 1 GeV do imply a far harsher possible environment than might have previously been assumed using the SEPEM model but remains lower (>factor 2 at >100 MeV) than values calculated using other models such as PSYCHIC (Xapsos et al., 2004) and JPL (Feynman et al., 1993).

Table 3: Comparison of results with and without NM Data (at 95% confidence level).

Energy (MeV)	1 year fluence (cm^{-2}.sr^{-1}) SEPEM	+ NM	% diff	3 years fluence (cm^{-2}.sr^{-1}) SEPEM	+ NM	% diff	7 years fluence (cm^{-2}.sr^{-1}) SEPEM	+ NM	% diff
> 10	1.83E+09	1.89E+09	3.0	3.69E+09	3.81E+09	3.2	6.71E+09	6.91E+09	3.0
> 30	2.76E+08	2.68E+08	-3.1	5.50E+08	5.52E+08	0.4	9.79E+08	9.85E+08	0.6
> 50	8.44E+07	9.35E+07	10.8	1.68E+08	2.02E+08	20.3	2.97E+08	3.58E+08	20.4
> 100	1.63E+07	2.24E+07	37.6	3.21E+07	5.13E+07	59.7	5.70E+07	9.05E+07	58.7
> 200	3.15E+06	5.38E+06	70.9	6.16E+06	1.31E+07	112	1.09E+07	2.29E+07	109
> 350	8.35E+05	1.70E+06	103	1.63E+06	4.33E+06	166	2.89E+06	7.55E+06	162
> 500	3.58E+05	8.15E+05	127	6.95E+05	2.14E+06	208	1.23E+06	3.72E+06	202
> 750	1.37E+05	3.53E+05	158	2.65E+05	9.61E+05	263	4.70E+05	1.67E+06	254
> 1000	6.92E+04	1.95E+05	182	1.33E+05	5.45E+05	309	2.37E+05	9.42E+05	297

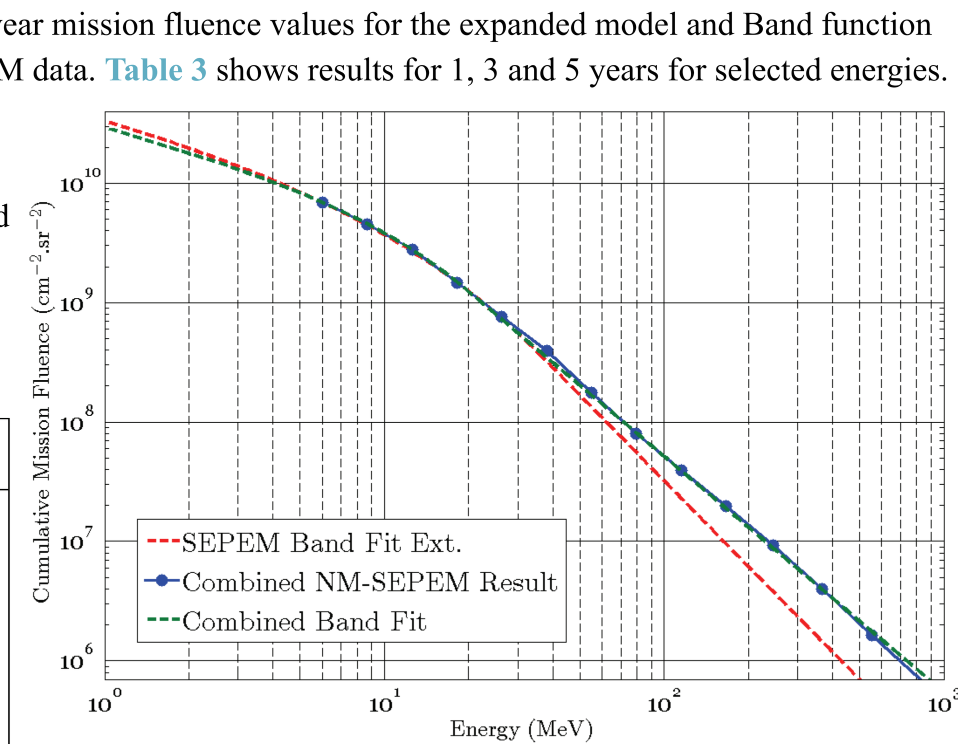


Figure 5: Comparison of 3-year cumulative mission fluence results at 95% confidence with an without NM data.

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Related work: Poster presentation: *Evaluating the effect of proton anisotropies in the inner heliophere: 2006 December 13 SEP event case study* (**A. Aran,** Session **9**) and **Oral presentation:** *Updates to the ESA Interplanetary and Planetary Radiation Model for Human Spaceflight* (**D. Heynderickx,** Session **14**)