Solar proton radiation during an interplanetary space mission

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Abstract: SEPs events are a serious hazard for both spacecraft and humans during interplanetary space missions. In this work, we use the ESA's SEPEM tool for statistical modelling the cumulative and the worst case proton fluences over the missions Helios 1 and Helios 2. We compute their energy spectra for periods of the solar cycle over the mission duration and fit them to most common distributions. We analyse the best fitting function for each case. Finally, we compare the cumulative fluence energy spectra of the model results at a 90% confidence level with data measured by the Helios 1 and 2 spacecraft.

I. INTRODUCTION

Solar Energetic Particles (SEPs) are the collection of electrons, protons, alpha particles and heavier ions up to iron in the interplanetary space, coming from the Sun with energies from tens of keV to a few GeV.

SEPs events result from the acceleration of these high-energy particles, caused either by: solar flares with a small flux increase in SEPs in the case of short-duration or impulsive events, or by interplanetary shock waves from Coronal Mass Ejections (CMEs) associated with a high increase of the particle intensity, mainly of solar protons, that may last several days. These large SEPs events are often related to long duration soft X-ray emissions and are called gradual events.

Many astrophysics and engineers have a strong interest for SEP events because they pose a serious risk for both spacecraft instruments and human health during an interplanetary space travel. Actually even airborne and ground-based systems can be damaged by severe SEP events such as the "Halloween Events" in 2003 [3].

Thus we need an accurate estimation of the occurrence probability of a SEP event during an interplanetary space mission, as well as its peak intensity and mission fluence, in order to minimize any irreparable radiation damage, no matter how close to the Sun we are.

A. SEPEM

One powerful tool to study SEPs events is the Solar Energetic Particle Environment Modelling (SEPEM) application server of the European Space Agency (ESA), a WWW interface developed by an international consortium, including the University of Barcelona [2]. It provides recent scientific advances and a complete set of cross-calibrated data from 1973 to 2013 that allows the creation and updating of many SEP engineering models and widgets. Moreover, SEPEM includes SEP statistical and physical modelling techniques that cover also the inner heliosphere (from 0.2 AU to 1.6 AU) using a recent Shock-and-Particle physics-based model to simulate particle flux profiles of gradual SEP events [1, 6].

B. Helios 1 and 2

Helios 1 and 2 were two unmaned solar probes launched on December 10,1974, and January 15,1976, respectively, from Cape Canaveral, Florida.

It was a cooperation project between West Germany's space agency and the NASA in order to collect useful data for the study of solar processes such as solar wind, Sun's magnetic field or cosmic rays [5].

Both spacecraft were put into heliocentric orbit as shown in FIG. 1. But Helios 2 went 3 millions of kilometres closer to the Sun than Helios 1, reaching its perihelion on April 17, 1976 at a record distance of 0.29 AU, even closer than Mercury's orbit.

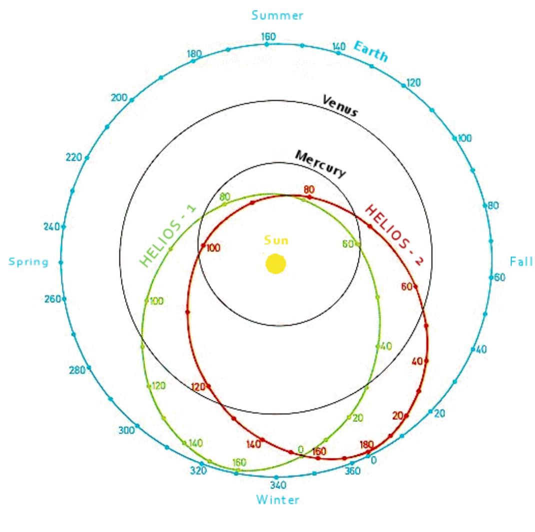

FIG. 1: Helios 1 and 2 orbits, with dates shown as days since the launch of Helios 2. Picture from NASA - Helios Gallery.

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II. SEPEM: AWAY FROM 1 AU

SEPEM provides a unique tool, called "Away from 1 AU" to predict the peak flux, worst-case event fluence and cumulative fluence for interplanetary missions, using a statistical modelling that includes the dependence on the radial distance to the Sun. For this purpose, SEP events are defined as starting when the differential flux in the second energy channel (7.23 – 10.46 MeV) went above 0.01 $\mathrm{cm^{-2}s^{-1}sr^{-1}MeV^{-1}}$, so that we can assume that we will detect relevant flux increases in SEPs over all solar periods. Each 11 year solar cycle has a maximum and minima periods of 7 and 4 years, respectively. The differential flux is known as the number of SEPs passing through a specified area and solid angle, in a certain time at a given energy window.

A. Model selection and parameters

As explained by *Jiggens et al.* in [4], the SEPEM statistical method produces a large number of virtual timelines instead of using the classical Monte Carlo simulation. The event list used is the SEPEM reference event list, based on SEP events measured at 1 AU [1].

In general terms, the Lévy distribution for the waiting times distribution is used to randomly select the initial time of the first event. Then the exponential cut-off power law is randomly sampled to determine the fluence (or peak flux) of the event. This fluence (peak flux) is used to find the fitted event duration randomly scattered as if the spacecraft were at 1 AU. The fluence (peak flux) of the SEP event is scaled for the spacecraft distance to the Sun at that time interval and it is stored. After that, the second waiting time is generated again by the Lévy distribution, as well as the event duration and the fluence accumulated (or the peak flux compared to the maximum one until then).

This process is repeated until the summ of all waiting times and event duration (the virtual timelines) achieve the total mission duration specified. The highest peak flux, the largest event fluence and the cumulative fluence generated for all events are saved in a vector of length equal to the number of iterations made (approx. 10^5), so that it provides three different model results:

- *The worst-case peak flux*: the highest flux that will not be exceeded over the complete mission length at a given confidence level.
- *The worst-case event fluence*: the fluence (or integral flux) that will not be exceeded by any single SEP event during the mission at a given confidence.
- *The cumulative mission fluence*: the fluence that will not be exceeded over the whole mission at a given confidence.

Once we have selected those parameters and desired distributions, we may provide the complete Helios spacecraft orbit (with date, time and corresponding radial distance from the Sun in AU) in the "Mission time steps" box. Intensity thresholds for determining the SEP events in each of the 11 energy channels may be specified (from the 1st: $5.00-7.23$ MeV to the 11th: $200.0-289.2$ MeV, which can be represented by the geometric mean of the highest and lowest energy in each range), or otherwise the thresholds would be defaulted by the system as we opted in our simulation.

B. Model results

The model outputs allow us to compare the results for three different cases according to the dependence on radial distance, which we label in this work as:

- *1 AU*: No distance scaling, that is the fluence and flux at 1 AU is directly used.
- *ECSS*: Based on the European Cooperations for Space Standardization's notes on November 15, 2008, that states that the results of SEPs models shall be scaled by a factor r^{-2} if the helioradial distance is less than 1. Otherwise, there is no distance scaling.
- *SEPEM*: The SEPEM method for distance scaling based on the SOLar Particle ENgineering Code (SOLPENCO2), developed from the Shock-and-Particle model [1].

As an example of this, FIG. 2 shows the fluence at 1 AU for the 1st energy channel (5.00 – 7.23 MeV) at a 90% confidence level with the Helios 1 orbit overlaid. As expected, we can check that higher values of accumulated fluence correspond to the solar maximum period.

III. FLUENCE ENERGY SPECTRA

The energy spectrum over an interplanetary mission is crucial to spacecraft engineering in order to evaluate any kind of radiation hazard at a certain confidence level.

The most common distributions for fitting such energy spectra are double power-laws, exponential cut-off power laws, or Weibull distributions [7]. For each solar period of both Helios missions, as well for the total mission duration, we fitted the corresponding differential fluence energy spectra to the above distributions. We used a nonlinear regression routine in Mathematica, called "NonlinearModelFit", in order to get a visual and numerical comparison of models to data thanks to log-log plots and some fitting parameters such as the correlation coefficient r. It was remarkable that the Weibull distribution was the best fit to every solar period in both Helios, closely followed by the exponential cut-off power law.

In fact, this predilection for the Weibull distribution was reviewed by *Xapsos et al.* [7], who pointed out its good fit to solar proton energy spectra, both for the fluence and the flux over a wide range of energies. Moreover, they recommend the following differential energy spectrum for solar proton events:

$$\frac{d\phi}{dE} = \phi_0 k \alpha E^{\alpha-1} \exp(-kE^{\alpha}), \tag{1}$$

where $\frac{d\phi}{dE}$ represents either the differential fluence (in units of $\mathrm{cm^{-2}sr^{-1}MeV^{-1}}$) or the differential flux (in $\mathrm{cm^{-2}s^{-1}sr^{-1}MeV^{-1}}$) at a given energy E (in MeV).

In next two sections, as in Xapsos' paper, we are going to show that actually the Weibull distribution is the best fit for both the cumulative fluence and the worst case event fluence, as we remarked before.

We note that the following fluence energy spectra are represented in a log-log scale from fluence values with a 90% confidence level. In all of them there are the three distance scaled fluences, denoted in the same way as in the previous section and coloured as indicated in the plot legend.

A. Cumulative fluence spectra

We can show, for example, the energy spectrum of both the maximum and minimum periods of the solar cycle 20 (the 20th solar cycle from the start of solar sunspot data recording) covered by Helios 1.

We can observe that the last point of both FIG. 3 and FIG. 4 was omitted in the fit by previous visual inspection. In fact, for the corresponding energy channel (the 11th), there are several events showing intensities with an intensity below the background level so it is recommended to ignore it (A. Aran private communication).

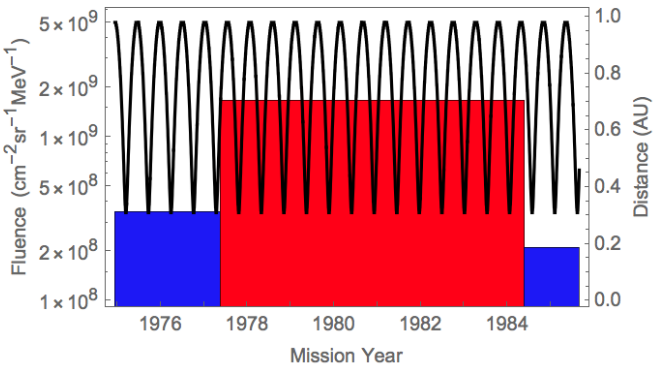

FIG. 2: Cumulative fluence for the 1st energy channel at 90% confidence level. In the left axis, the fluence contribution at 1 AU for each solar period over Helios 1 (10.72 years). Minimum and maximum periods correspond to blue and red blocks, respectively. In the right axis, the distance in AU of the mission orbit overlaid in black.

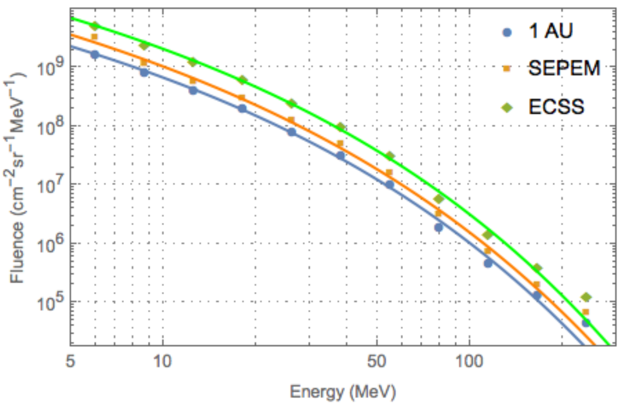

FIG. 3: Comparison of Helios 1 data (over the complete solar maximum 21 of 7.00 years) for the differential fluence energy spectrum (points) to the best fitting Weibull distribution (solid lines).

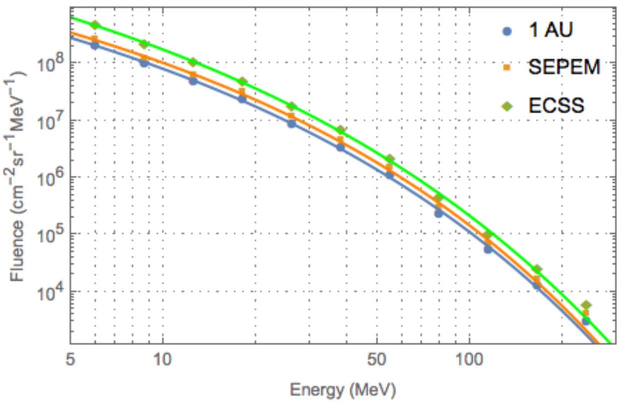

FIG. 4: Comparison of Helios 1 data (over the first 1.27 years of the solar minimum 21) for the differential fluence energy spectrum (points) to the best fitting Weibull distribution (solid lines).

Later in FIG. 6 and FIG. 8, the corresponding Weibull distributions are shown for both missions.

Finally, in TABLE I we present the three fitting parameters for the total mission duration of each Helios.

	Helios	ϕ_0 [$\mathrm{cm^{-2}sr^{-1}}$]	k [$\mathrm{MeV^{-\alpha}}$]	α
1 UA	1	1.577 x 10^{11}	1.307	0.4051
	2	7.381 x 10^{10}	1.281	0.4077
SEPEM	1	2.754 x 10^{11}	1.408	0.3928
	2	1.057 x 10^{11}	1.290	0.4066
ECSS	1	4.516 x 10^{11}	1.277	0.4093
	2	2.076 x 10^{11}	1.301	0.4069

TABLE I: Weibull fitting parameters for both Helios 1 and Helios 2 (over 10.72 and 4.15 years, respectively) and for each distance scaling method, with $r^2 = 0.9999$.

B. Worst case event spectrum

Although in next section we will need only the cumulative case, we show in FIG. 5 an example of a worst case event spectrum for the sake of completeness. In fact, again the Weibull distribution is a good fit for all solar periods covered by the mission.

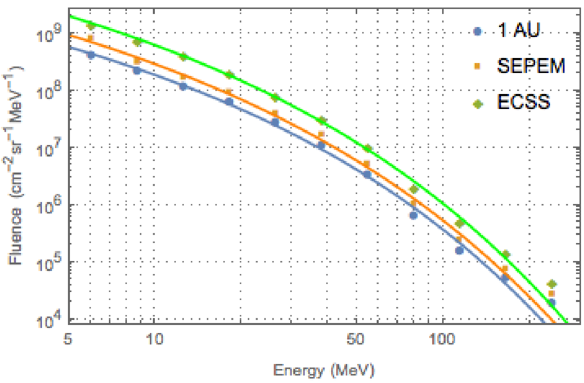

FIG. 5: Comparison of Helios 2 simulation over the complete mission (4.15 years) for the differential fluence energy spectrum (points) to the best fitting Weibull distribution (solid lines) with the worst case event results.

Let us mention at this point a possible programming error in the code of the SEPEM application we found for the solar minimum 20 (1.36 years) in the Helios 2 simulation. In this case, the model outputs give the same fluence for all three distance scaling methods. This makes us think about a code error in the first minimum period in Helios 2 orbit because in the case of Helios 1, for a period of the same duration during the solar minimum, there was no overlap. Therefore, this needs further investigation.

Anyway, this possible bug in the minimum period does not really affect the energy spectra for the complete Helios 2 mission because it is dominated by the higher maximum period fluence, which has not that error.

IV. COMPARISON OF MODEL RESULTS WITH MEASURED DATA

Such as for all physical models, it is important to compare the model results and measured data in order to verify that there are no significant discrepancies over the whole range. It is also a helpful tool for engineers to make a realistic prediction of radiation damage level that will encounter new devices at a desired confidence level.

For this reason, here we compute the cumulative mission energy spectra for both Helios 1 and Helios 2 from the data compiled directly by the spacecraft instrumentation over the total mission length (data facilitated by A. Aran). An instance of these data is shown in FIG. 7, where we can distinguish four energy channels and some data gaps that we find over the mission duration.

First, we calculate the background intensity level as the data mean over the four energy channels during a quiet mission period, and we get: $B_1 = (2.00 \pm 0.04)\ 10^{-4}$ cm^{-2}s^{-1}sr^{-1}MeV^{-1} for Helios 1 and $B_2 = (1.71 \pm 0.03)\ 10^{-4}$ cm^{-2}s^{-1}sr^{-1}MeV^{-1} for Helios 2. Thus for next analysis we will omit those intensities that are below this background level.

Then we compute the cummulative fluence over both complete missions in the following way:

$$F_x = \sum_i (t_{fi} - t_{0i})(I_i - B_x), \tag{2}$$

where F_x is the differential fluence (in units of cm^{-2}sr^{-1}MeV^{-1}) for either Helios 1 ($x = 1$) or Helios 2 ($x = 2$), B_x is the corresponding background level, I_i is the intensity (in cm^{-2}s^{-1}sr^{-1}MeV^{-1}) for each time interval $[t_{0i}, t_{fi}]$ (in seconds) over the mission timeline, divided into steps of approx. 1 h.

Finally we show the energy spectra for both Helios 1 in FIG. 6, and Helios 2 in FIG. 8. We note that the errors calculated by propagation are small.

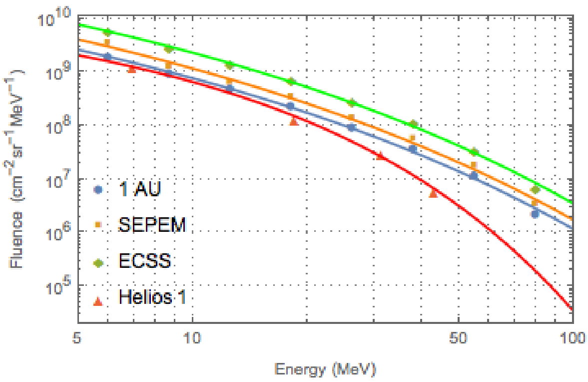

FIG. 6: Comparison of data collected by Helios 1 (red points) over the complete mission duration (10.72 years) to model results from the mission simulation. Each data set again fitted to a Weibull distribution as in former sections.

Therefore we verify that the cumulative fluence energy spectra for data collected for both Helios are below all three energy spectra corresponding to the different distance scaling methods given by the model results. That is what we might have expected since at a 90% confidence level, so that the probability of exceeding a given predictive cumulative mission fluence value should be only a 10%. From further inspection, we realized that three last years of Helios 1 (from 1983 to 1985) were almost empty data so this could have overestimate model results. Anyway we ran again a simulation of Helios until 1983 and the results were very similar, though now the energy spectrum from measured data was just above (almost overlapping) the "1 AU" model spectrum but still below the cumulative fluence level predicted by the SEPEM radial scaling method. The ECSS method clearly overestimates the accumulated mission fluence for both spacecraft.

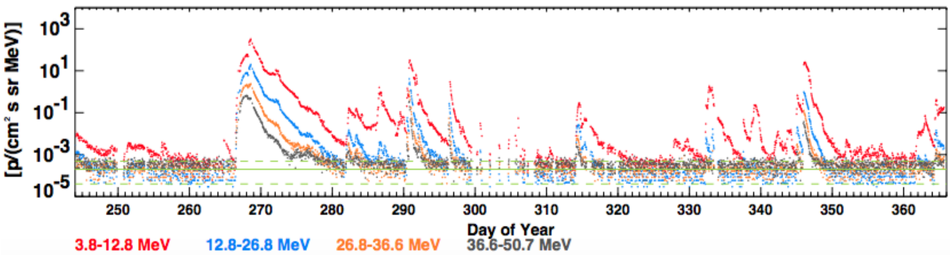

FIG. 7: Proton differential intensity data collected by Helios 1 over the year 1978 for 4 energy channels (corresponding colour in the plot legend) with a green solid line as the background level calculated.

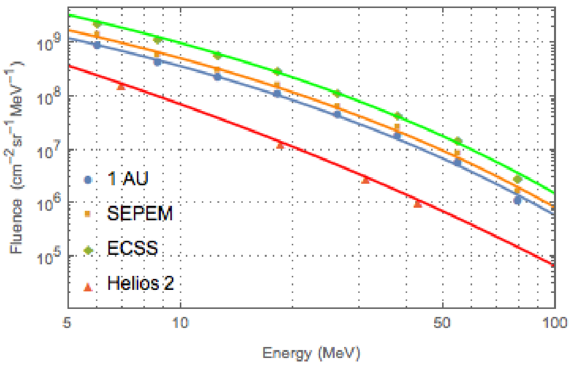

FIG. 8: Comparison of data collected by Helios 2 (red points) over the complete mission duration (4.15 years) to model results from the mission simulation. Each data set again fitted to a Weibull distribution as in former sections.

V. CONCLUSIONS

The importance of SEPs events' study for astrophysics and engineers lies in their serious effects to both spacecraft proper functioning and human health. For this purpose, there is the SEPEM application server with useful statistical and physical models over a long list of computer processed data.

In this work, we have fitted satisfactorily the energy spectra of Helios 1 and Helios 2 (as a result of the mission simulation in the SEPEM application server) to a Weibull distribution with three fitting parameters. In fact, we have verified that this is the proper distribution for each solar period (maximum or minimum) over the missions, as well as for the worst case event spectra and the cumulative ones.

At the end, we have compared these model results to data measured directly by Helios 1 and 2 spacecraft, verifying that the empirical cumulative fluence spectra for both missions are below when the actual orbit of the mission is considered (orange and green curves) in model energy spectra, as we expected at a 90% confidence level. It would be a good practice to fill the gaps in data collected by Helios 2 to check if it still remains below the model energy spectra since it seems that in this case we have more gaps in solar active years than in Helios 1.

Moreover, we have discovered a relevant error in the first minimum of Helios 2 since the model simulation does not distinguish between the three distance scaling methods, pointing out a possible code error that should be fixed since it could affect other simulations.

Further investigation on this point, as well as on filling data gaps, will be done in collaboration with A. Aran and her colleagues with the intention to write an article on the subject in the near future.

Acknowledgments

I would like to thank my advisor, Dr. Àngels Aran Sensat, for introducing me to SEPs event modelling's field and to the SEPEM application server, as well as for her support and guidance throughout this project.

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