SStoRM: the Solar Storm Radiation Model

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Abstract

NASA wrote the computer program BRYNTRN to calculate the radiation dose received by a person in outer space during a solar particle event (SPE). I ran this code for many parameters and wrote the GUI application SStoRM (Solar Storm Radiation Model) to make this output more accessible. SStoRM will be useful as a teaching and research aid in understanding the severity of SPEs as our nation embarks on future missions to the Moon, Mars and beyond.

Table of Contents

1. Introduction

As astronauts venture into outer space, they lose the protection of the Earth. The Earth's atmosphere and magnetic field shield humans from dangerous ultraviolet light and cosmic radiation. This radiation can mutate human DNA, resulting in both short-term and long-term damage.

Cosmic Radiation comes in two forms, galactic cosmic rays and solar particle events (SPEs). SPEs are of particular concern to astronauts because they can deliver large bursts of potentially fatal proton radiation over very short periods of time. As a result, the space community is studying these events with intense effort.

To aid in this endeavor, NASA wrote the computer program BRYNTRN to determine the radiation dose that an astronaut would receive in outer space during an SPE. The output of this code was compiled for many theoretical SPEs and used to write the graphical computer program SStoRM. SStoRM lets its user specify any SPE that they wish. It can then display in a clear and meaningful way the extent of the damage that this particular SPE would cause to an astronaut in outer space. This tool can be used to teach about how damaging SPEs can be.

2. Background Information

2.1. Galactic Cosmic Rays

Solar radiation comes in two forms. The first is Galactic Cosmic Rays (GCRs). GCRs are an ever-present source of radiation in outer space. Originating outside our solar system, GCRs consist of every natural element, but 90% of GCR radiation comes from hydrogen and 9% comes from helium. GCRs consist of high energy particles, and as such can be quite penetrating through even thick layers of shielding. Despite their high energy, there is not enough of it to cause short-term harm. The real danger of GCRs is from long term exposure that can increase the risk of long term problems such as sterility and cancer.

2.2. Solar Particle Events

Radiation also arises from Solar Particle Events (SPEs). SPEs are primarily proton radiation that is emitted from the sun. SPEs are quite different from GCRs because they are relatively infrequent and short lived. Nevertheless, they can cause great short-term damage to astronauts in outer space. They are dangerous because, even though they are short lived, they deliver a high fluency (number of radioactive particles). Therefore, they can lead to severe short-term radiation damage such as headaches, dizziness, nausea, vomiting, and possibly death.

It was previously thought that SPEs were caused by solar flares, but now it is becoming accepted that larger ones are caused by the shock created during fast coronal mass ejections (CME). A CME causes a shockwave that pushes protons at high speeds into the solar winds. These protons (as well as some other particles) are what create SPEs.

The frequency of solar particle events varies with the solar cycle, but there can are usually ten to twenty significant SPEs within a ten-year cycle with up to four being able to cause potential harm to astronauts.

2.3. Harm from Radiation

Radiation dose is defined as the amount of energy absorbed by an amount of mass. The standardized unit of dose is a gray. One Gray is defined as one Joule of energy absorbed by one kilogram of mass. Because certain types of radiation can be more harmful than others, a new unit was formed, the Sievert (Sv). The Sievert measures the dose equivalent. It includes a quality factor that accounts for the difference in harmfulness of various types of radiation. The general equation is:

Dose Equivalent = Absorbed Dose x Quality Factor

The quality factor of radiation doses from SPEs will range from about 1.5 to more then 2.5 depending upon the type and energy of the particles involved in the event.

Through detailed research, certain legislative and biological limits have been determined concerning the amount of radiation that a person can safely withstand. NASA also works off of the ALARA principal: As Low as Reasonably Achievable. This states that any steps that can reasonably be taken to lower the radiation dose received by a person should be taken.

Legislative limits are in the form of monthly limits, annual limits, and career limits. They are conservative and should be thought of only as an absolute upper ceiling. The National Council on Radiation Protection and Measurements (NCRP) has stated that the 30 day radiation limit to the bone marrow (BFO) is 25 cSv, the annual limit is 50 cSv and the lifetime limit varies depending on gender and age, but ranges from 100 cSv to 400 cSv.

In addition to legislative limits, there are biological limits to the amount of radiation that someone can withstand. Biological limits describe how one's body will react when exposed to radiation. Table 1 presents biological limits as defined by the United States Armed Forces Radiological Research Institute's Medical Management of Radiological Casualties Handbook.

35 – 75 cGy	Nausea; mild headache
75 – 125 cGy	5 to 30 % experience nausea and vomiting within 3 to 5 hrs
125 – 300 cGy	20 to 70 % experience nausea and vomiting within 2 to 3 hrs. 5 to 10 % probability of death with no treatment.
300 – 530 cGy	50 to 90 % experience nausea and vomiting within 2 hrs. 10 to 50 % probability of death with no treatment.
530 – 800 cGy	50 to 90 % mild to severe nausea and vomiting within 2 hrs. 50 to 90 % probability of death with no treatment.

Table 1: Biological radiation exposure limits

These units are in grey, a measure of absorbed dose. Because solar proton radiation affects the body in a qualitatively different way than gamma radiation, used to create these biological limits, there is some concern that these limits do not translate well to dose from an SPE.

3. The Theoretical SPE

3.1. The Energy Spectrum

AN SPE is a large storm composed mainly of protons. Each proton has an energy, or speed, measured in MeV (Mega Electron Volt). A frequency distribution of energy values produces a particle distribution (also called an energy spectrum or spectral curve). The shape of this energy spectrum turns out to be one of the defining characteristics of an SPE. Figure 1 is an example of the particle spectrum for a particularly severe SPE that occurred in August 1972.

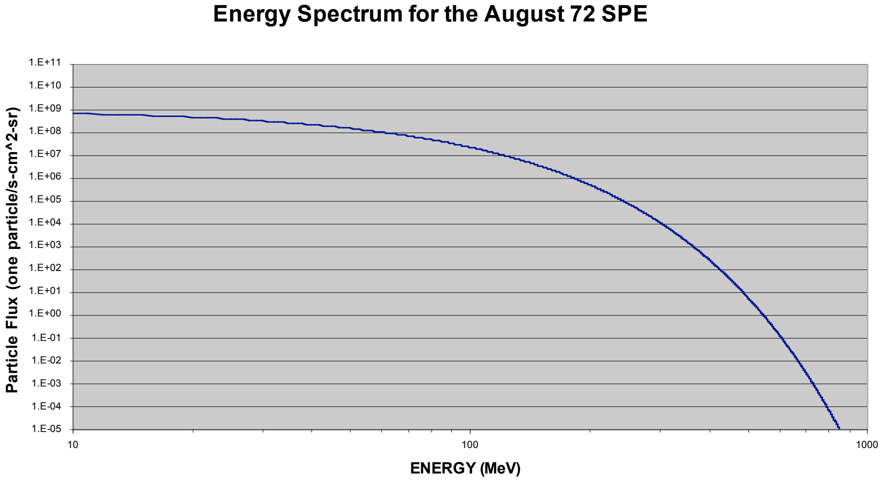


Figure 1: An Example Particle Spectrum.

The following exponential curve equation does a good job describing the spectral curve of previously observed SPEs.

$$Fluence(E) = K \times E^{-\gamma} \times e^{-E/E_0}$$

This is not as bad as it looks. K, γ, and E_0 are free parameters that define the energy spectrum. γ and E_0 work to define the shape of the curve while K scales the curve up and down. For example, a K of $9.2\text{x}10^9$, a γ of 0 and an E_0 of 26.5 fits the august 72 event's energy spectrum particularly well. We can integrate the flux equation as follows:

$$IntegralFluence(E_{\min}) = \int_{E_{\min}}^{\infty} Fluence(E)dE$$

The integral flux represents the total number of protons that an SPE has above a given energy value ($E_{\min}$).

3.2. The Time Evolution

The other defining characteristic of an SPE is its time evolution. The time evolution of an SPE is a curve of integral proton flux as a function time. An example time evolution curve appears in figure 2.

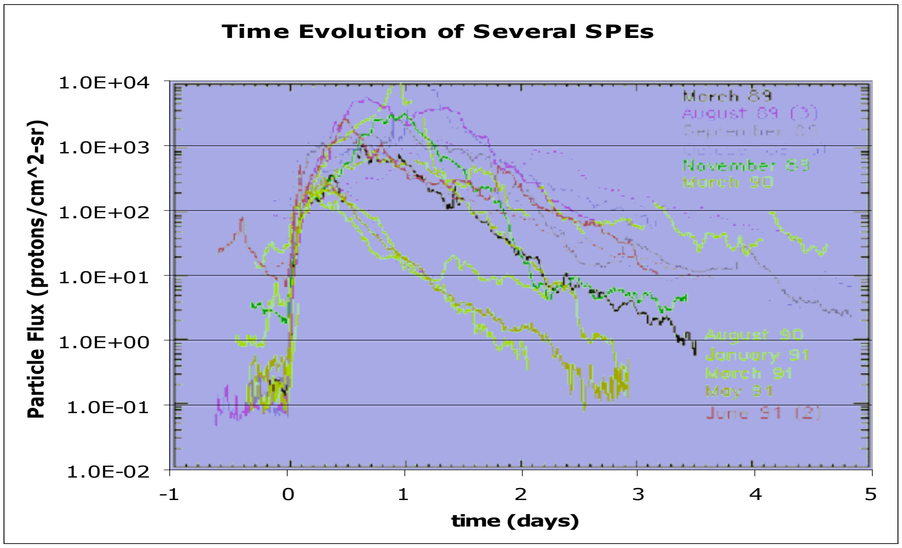


Figure 2: Time evolution of several historical SPEs.

A convenient way to define the time evolution of an SPE is with the following equation:

$$Flux = \mathbf{C}\left(\frac{\mathrm{t}}{\mathrm{A}}\right)^{B1} e^{-\left(\frac{t}{A}\right)^{B2}}$$

Here, C, A, B1, and B2 are free parameters that define the time evolution of an SPE. B1 and B2 define the general shape of the curve. The A parameter acts to expand and contract the time interval of the event. C works, like K, to scale the SPE’s intensity. We can also define the integral flux of the time evolution of the event.

$$IntegralFlux = \int_0^{end} \mathbf{C}\left(\frac{\mathrm{t}}{\mathrm{A}}\right)^{B1} e^{-\left(\frac{t}{A}\right)^{B2}}$$

Here, the integral flux of the time evolution of the event also represents the total number of protons. Because the time evolution and energy spectrum of an SPE both measure similar quantities, they are slightly redundant and it can be shown that one of the constants (C or K) is not necessary to define a single SPE.

3.3. About BRYNTRN

BRYNTRN is a computer program written in FORTRAN by NASA. It was created to simulate the effects of solar radiation on astronauts. It “transports SPE protons and their reaction products (protons, neutrons, deuterons, tritons, hellions, and alphas) through the aluminum shield material and body tissues overlying the critical organs of interest” (Townsend, the Carrington Event). It can do so through every angle of the human body using the Computerized Anatomical Man (CAM) model. It is also very flexible. It will simulate an SPE defined by any energy spectrum and aluminum thickness desired. It gives both absorbed dose and dose equivalent to the skin, ocular lens (eye), and bone marrow (BFO).

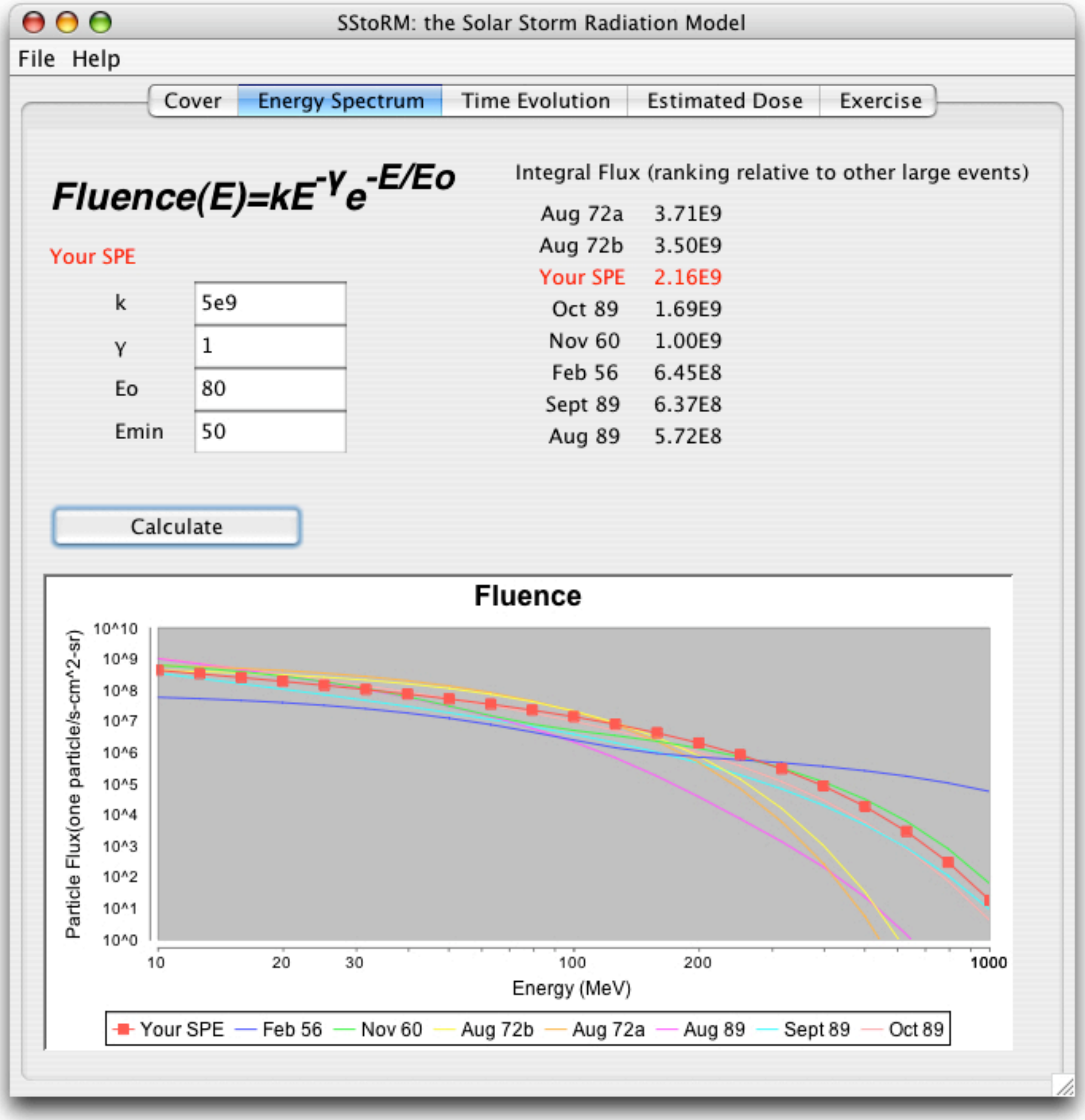
To simulate a generic SPE, BRYNTRN was run for a variety of γ values, E_0 values, and thicknesses. More precisely, BRYNTRN was run for the γ values 0, .125, .25, ... all the way up to 4.125. For each γ value, E_0 was run from 10, 20, 30, …, all the way up to 500. Most typical SPEs will fall within this range. For doses that fall between selected values, a bilinear interpolation can be used to accurately estimate what the values should be. For each γ and E_0, an aluminum shielding thickness of 0.3 g/cm^2, 1 g/cm^2, 5 g/cm^2, 10 g/cm^2, and 30 g/cm^2 was used to calculate radiation dose. This resulted in 25,500 different radiation dose values. 0.3 and 1 g/cm^2 were chosen because they represents typical space suit shielding thicknesses, 5 g/cm^2 because it represents a typical lightly shielded vehicle such as a lunar rover, 10 g/cm^2 because it represents a typical spacecraft, and 30 g/cm^2 because it represents a typical safe haven that an astronaut could protect himself under during an SPE.

4. SStoRM

SStoRM, the Solar Storm Radiation Model, is a JAVA application written to present all of the output from BRYNTRN in an intuitive manner. Because it is written in JAVA, SStoRM is a cross platform application. It has been tested with Windows and Mac OS X. For this report, screenshots are presented as it appears when run by a Mac. SStoRM allows the user to decide what they want an SPE to look like. They can choose both the energy spectrum and the time evolution of the event. From that, they can read the dose received by the astronaut and do a small exercise that puts astronauts on the moon during an SPE and has them stop their current work and leave for shelter.

4.1. Selecting the Energy Spectrum

To use SSoRM, one must first specify the energy spectrum of an SPE. The interface for selecting the energy spectrum is shown in Screenshot 1.



$Fluence(E)=kE^{-\gamma}e^{-E/Eo}$

Your SPE

k = 5e9
γ = 1
Eo = 80
Emin = 50

Integral Flux (ranking relative to other large events)

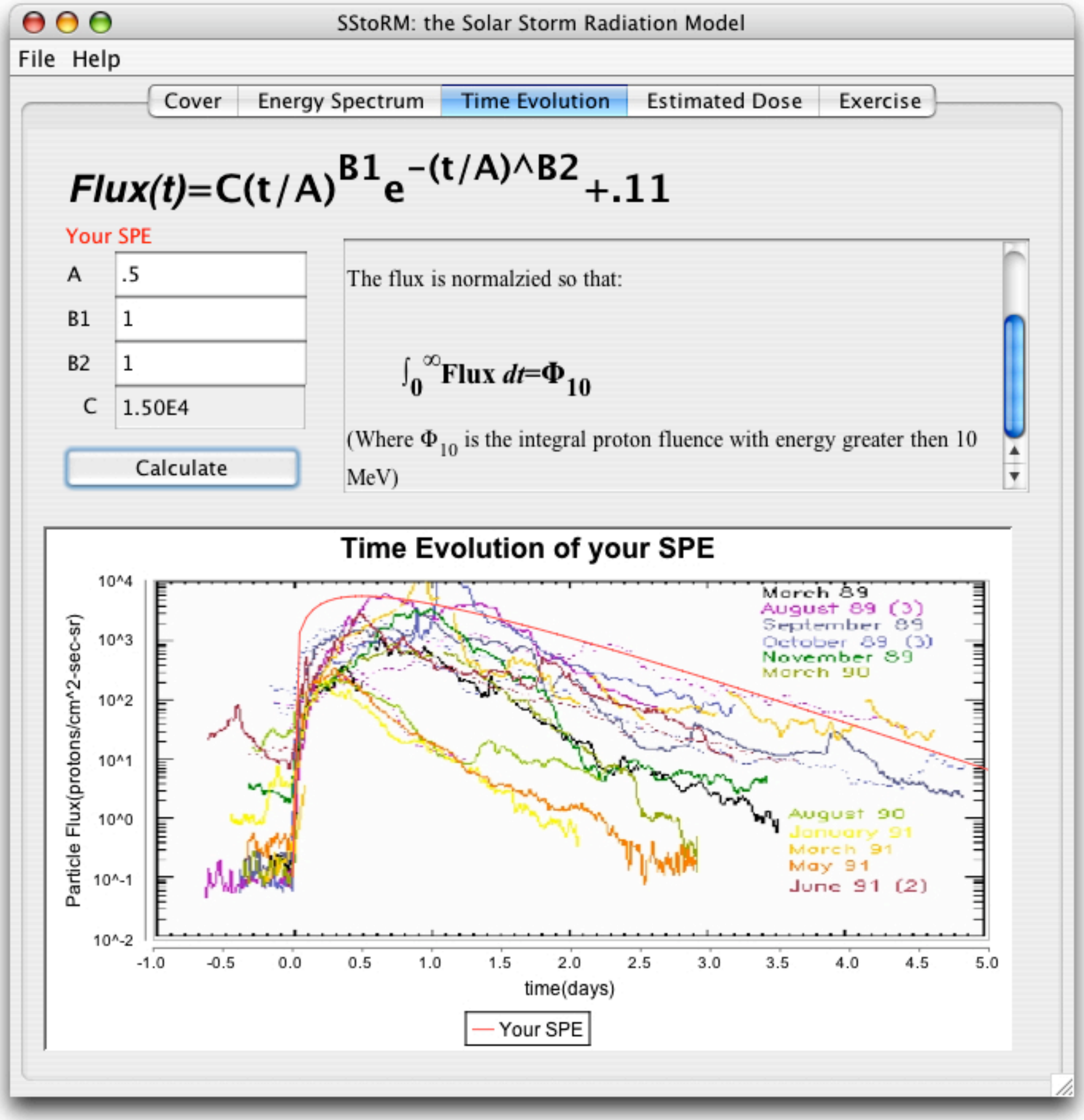
Aug 72a	3.71E9
Aug 72b	3.50E9
Your SPE	2.16E9
Oct 89	1.69E9
Nov 60	1.00E9
Feb 56	6.45E8
Sept 89	6.37E8
Aug 89	5.72E8

Screenshot 1: Selecting the energy spectrum of "your SPE".

SStoRM allows the user to specify the K, γ, and E_0 parameters of the event. They also get to specify E_{min}, or the minimum energy value to integrate from when finding the integral flux. When the calculate button is pressed, the flux is graphed along with the spectral curve of several historical SPEs. This graph helps the user pick realistic parameters. The integral flux for all the graphed curves is compared in the chart to the right.

4.2. Selecting the Time Evolution

SStoRM then lets the user specify the time evolution of their SPE. Screenshot 2 shows this process.



$$Flux(t)=C(t/A)^{B1}e^{-(t/A)\wedge B2}+.11$$

Your SPE

A .5

B1 1

B2 1

C 1.50E4

The flux is normalzied so that:

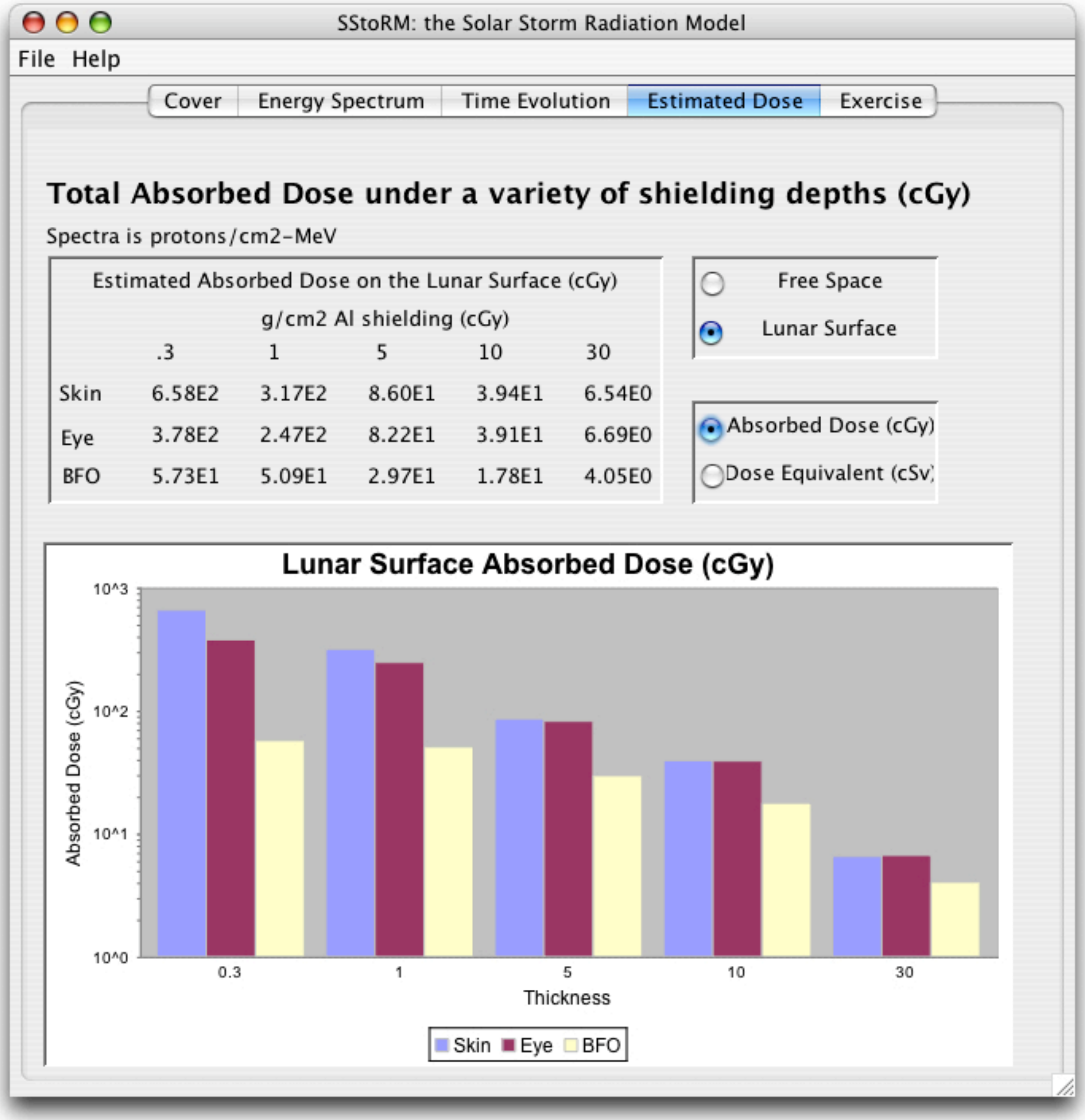
$$\int_0^{\infty} \text{Flux } dt = \Phi_{10}$$

(Where Φ_{10} is the integral proton fluence with energy greater then 10 MeV)

Screenshot 2: Selecting the time evolution of "your SPE".

Here, the user can select A, B1, and B2, the parameters of the time evolution curve. They are not given the choice of selecting C. Instead, C is calculated automatically to ensure that the integral flux of the time evolution of the event is the same as the integral flux of the energy spectrum of the event. Once the calculate button is pressed, the C factor and the graph of the time evolution of the event are displayed.

4.3. Reading the Estimated Dose



Total Absorbed Dose under a variety of shielding depths (cGy)

Spectra is protons/cm2-MeV

Estimated Absorbed Dose on the Lunar Surface (cGy)

	g/cm2 Al shielding (cGy)				
	.3	1	5	10	30
Skin	6.58E2	3.17E2	8.60E1	3.94E1	6.54E0
Eye	3.78E2	2.47E2	8.22E1	3.91E1	6.69E0
BFO	5.73E1	5.09E1	2.97E1	1.78E1	4.05E0

○ Free Space
● Lunar Surface

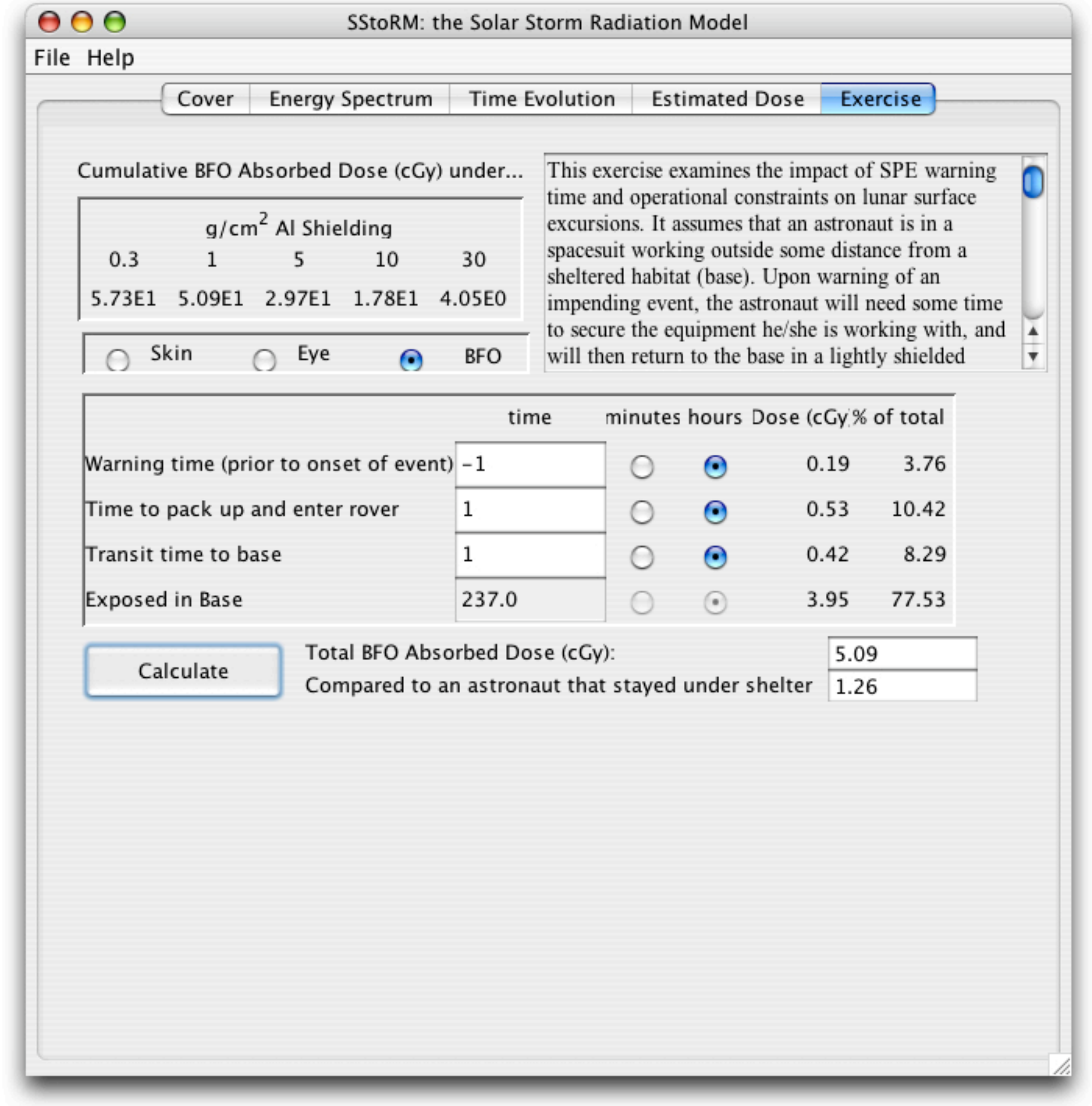
● Absorbed Dose (cGy)
○ Dose Equivalent (cSv

Screenshot 3: The dose output from BRYNTRN.

Screenshot 3 shows the next section of SStoRM, the estimated dose tab. This is the most important part of the program. It presents the dose output of BRYNTRN based on the given K, γ, and E_0 parameters of the energy spectrum. SStoRM gives total event dose to the Skin, Eye, and BFO. It does so for thicknesses .3, 1, 5, 10, and 30 g/cm^2. The radio buttons let the user select absorbed dose or dose equivalent and dose in free space or dose on the lunar surface. The difference is that the dose on the lunar surface is half of the dose in free space. This is because the moon blocks out half of the rays of radiation that could hit the astronaut.

4.4. The Final Exercise

Once the energy spectrum, time evolution, and radiation doses are calculated for the selected SPE, the user is presented with a fun exercise. This is shown in Screenshot 4.



Cumulative BFO Absorbed Dose (cGy) under...

g/cm^2 Al Shielding				
0.3	1	5	10	30
5.73E1	5.09E1	2.97E1	1.78E1	4.05E0

○ Skin ○ Eye ● BFO

This exercise examines the impact of SPE warning time and operational constraints on lunar surface excursions. It assumes that an astronaut is in a spacesuit working outside some distance from a sheltered habitat (base). Upon warning of an impending event, the astronaut will need some time to secure the equipment he/she is working with, and will then return to the base in a lightly shielded

	time	minutes	hours	Dose (cGy	% of total
Warning time (prior to onset of event)	-1	○	●	0.19	3.76
Time to pack up and enter rover	1	○	●	0.53	10.42
Transit time to base	1	○	●	0.42	8.29
Exposed in Base	237.0	○	●	3.95	77.53

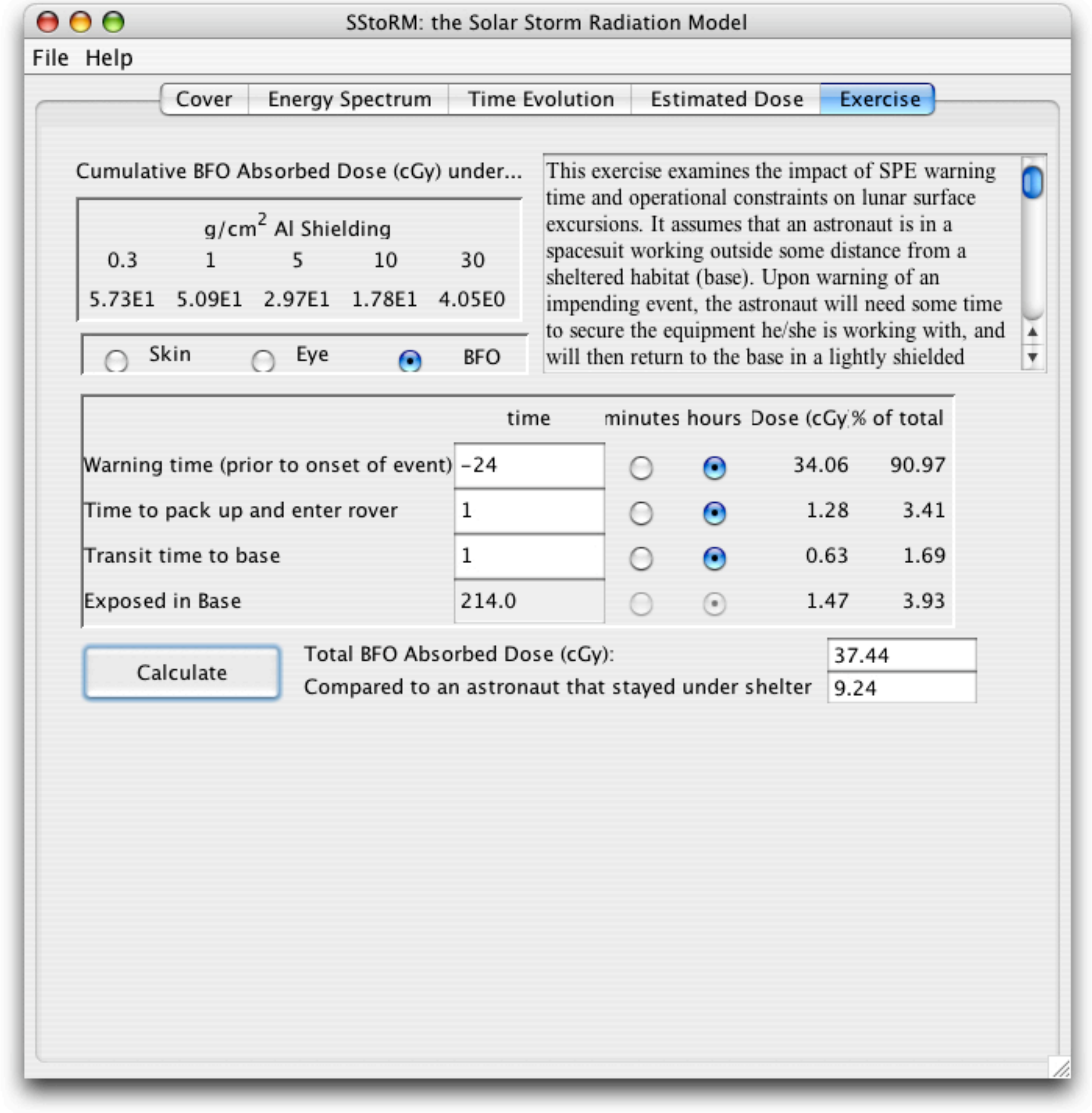
Total BFO Absorbed Dose (cGy): 5.09
Compared to an astronaut that stayed under shelter 1.26

Screenshot 4: The exercise in SStoRM.

This exercise allows the user to simulate an astronaut working on the moon during an SPE. The user can select a warning time that an astronaut would receive prior to the onset of the event. A negative value means that they are warned about the SPE that many hours after the event has started. They then take a given time to pack up and enter the rover. During this time, they are under a .3g/cm^2 aluminum shielding thickness. They then drive back to the base under a 5 g/cm^2 shielding thickness. Once at base, they stay under a heavy shielding of 30 g/cm^2 for the remainder of the event.

For the particular example shown in Screenshot 4, the astronaut was warned about the event 1 hour after it began. It took an hour to pack up his gear and an hour to drive back to his base. He would receive 1.26 times as much radiation as having been inside heavy shelter during the entire event. When compared with biological limits, this radiation dose, 5.09 cGy, is not particularly severe.

Suppose, instead, that it took a day before the astronaut was given warning of the event. This scenario is presented in Screenshot 5.



Cumulative BFO Absorbed Dose (cGy) under...

g/cm^2 Al Shielding				
0.3	1	5	10	30
5.73E1	5.09E1	2.97E1	1.78E1	4.05E0

○ Skin ○ Eye ● BFO

This exercise examines the impact of SPE warning time and operational constraints on lunar surface excursions. It assumes that an astronaut is in a spacesuit working outside some distance from a sheltered habitat (base). Upon warning of an impending event, the astronaut will need some time to secure the equipment he/she is working with, and will then return to the base in a lightly shielded

	time	minutes	hours	Dose (cGy	% of total
Warning time (prior to onset of event)	-24	○	●	34.06	90.97
Time to pack up and enter rover	1	○	●	1.28	3.41
Transit time to base	1	○	●	0.63	1.69
Exposed in Base	214.0	○	●	1.47	3.93

Total BFO Absorbed Dose (cGy): 37.44

Compared to an astronaut that stayed under shelter 9.24

Screenshot 5: The exercise with different parameters.

This would increase the dose that the astronaut would receive to over 9 times that another one would receive at the base! He would now absorb over 37 cGy of radiation! This dose would cause him to experience headaches and mild nausea.

4.5. How the Exercise Works

To calculate the total dose that an astronaut would receive over a given period of time (from T_{start} to T_{end}) under a given thickness x and a cumulative dose $Dose_x$, the following formula is used to calculate a new C for the time evolution curve.

$$C_X = \frac{Dose_x}{\int_0^{10} fluxdt}$$

Here, the flux on the bottom of the equation assumes C=1. In essence, the new C is calculated for the time evolution flux by first normalizing it and then multiplying by the dose. This means that when we re-integrate the new time evolution flux from 0 to 10 days, we get the total dose. If we now integrate from any time period to any other time period, we get the dose received during only those hours. So the dose from T_{start} to T_{end} under a dose x is:

$$Dose = \int_{T_{start}}^{T_{end}} C_X fluxdt$$

SStoRM works by calculating a separate C for each thickness required during the exercise. It then integrates with each C for the hours desired. The doses are summed into the total dose that an astronaut would receive during the entire event.

5. Conclusion

Solar particle events will be an ever present source of danger to humans as they venture away from the planet Earth. With this in mind, SStoRM was written. It can help teach people about the inherent dangers of solar particle events and the unpleasant situations that they can put astronauts in. Hopefully, this tool will aid future planning and preparation for voyages to the Moon, Mars, and beyond.

6. Acknowledgements

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