Mayday, Mayday, Mayday!

by *Aviat-ions*

NASA Space Apps Challenge 2017

Athens, Greece

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1. Introduction

A widely known problem is the exposure of crew members and passengers to radiation especially near the polar regions.
This project calculates and visualises this radiation exposure during a certain flight. New models have been developed that take into consideration the interaction of solar particles and cosmic rays with Earth's magnetosphere and atmosphere. They calculate the radiation dose both at any time during a flight the total. Finally, this project shows the health risks and biological factors that come with this radiation exposure.

1.1 Cosmic Rays

The cosmic rays are a continuous bombardment of extremely energetic charged particles and gamma-photons that approach the earth. Some of them manage to penetrate the Earth's magnetosphere and atmosphere, exposing the crew members and passengers of aircraft flights to radiation. It is composed by 80% protons, 15% α-particles whilst the rest 5% is a combination of electrons, heavier ions and photons. They consist of three components: the solar, the galactic and the extragalactic component. While the second and third components are irrelevant to the sun, they appear to have opposite modulation to the solar eleventh year cycle (Figure 1). The explanation of this phenomenon is that during the solar maximum, the propagation of the solar wind blocks highly the cosmic rays from entering the heliosphere. The same phenomenon can happen for small time scales during the low activity period of the sun whenever there is an explosive solar activity such as a flare or a CME.

The only primary cosmic ray particles that can survive transport through the atmosphere and reach cruising altitudes of typical commercial aircrafts are protons with energy on the order of 1GeV or greater. The secondary particles are product of hadronic and electromagnetic showers with energy of 1GeV or higher. The nucleonic component of these secondary particles (protons and neutrons) is the most hazardous for human health, so these are the ones that will be taken into consideration for the calculations in this project. The high LET (Linear Energy Transfer) particles at 10-12km with energy E<1GeV are secondary particles, most of them neutrons, created at higher altitudes from nuclear fragmentation reactions. The heavy ions have largely disappeared due to a combination of ionization energy loss and nuclear fragmentation reactions into lower energy lighter particles. The particles with energy much greater than 10GeV, using the power law for cosmic rays $N \sim E^{-2.6}$, have much lower flux, so they do not contribute significantly to the radiation exposure. Therefore, we only take into consideration the cosmic ray protons and the secondary particles, product of hadronic showers (protons and neutrons) in the energy spectrum of 1GeV<E<10GeV.

For the absorption of cosmic rays the following was used as flux to altitude:

$$F(h)= 10^{\frac{10}{3}\log(h)-\frac{1}{3}},$$

where h is the altitude and F is the energy flux.

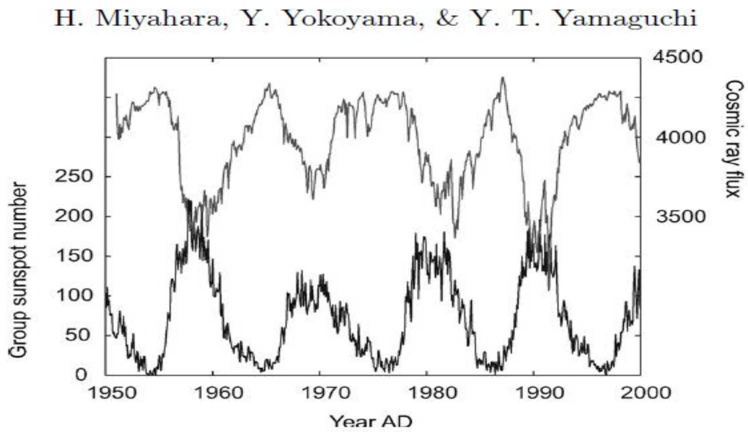

Figure 1. Monthly variation of eleventh year cosmic ray cycle (Miyahara H. et al, "Influence of the Schwabe/Hale solar cycles on climate change during the Maunder Minimum")

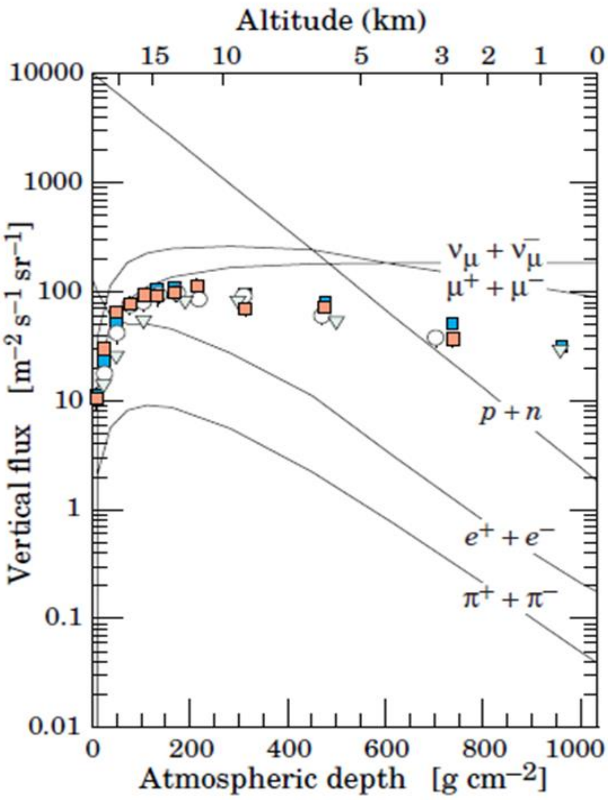

Figure 2. Flux of cosmic ray components as a function of atmospheric depth/altitude. The component that is taken into consideration in this project is the flux of neutrons and protons (Beatty J.J. et al., "Cosmic Rays", 2011)

1.2 Magnetosphere

The Earth's magnetosphere is a region around the planet dominated by the local magnetic field that shields our home planet from solar and cosmic particle radiation, as well as erosion of the atmosphere by the solar wind - the constant flow of charged particles streaming off the sun. The magnetic poles are different from the geographic poles and to be exact, they are opposite and they have an inclination of 11.5^{o}. Earth's magnetosphere is part of a dynamic, interconnected system that responds to solar, planetary, and interstellar conditions. The Sun facing side - dayside - extends a distance about 10 earth radii of earth whilst the night-side extends up to hundreds of earth radii. There, most of the phenomena of the solar wind start, ending to particle radiation to the polar cusps, exposing aviation and commercial flights to radiation. This exposure will be discussed in this chapter.

To discuss about the exposure, we need to know and take into consideration all solar phenomena that affect the magnetosphere. The most essential are the CME's, the solar flares and the continuous emission of solar wind towards the earth. These phenomena produce the SEP's (Solar Energetic Particles) that affect our magnetosphere. The intensity of these events goes accordingly to the solar cycle. The SEP's -consisting of electrons, rarely protons and in extreme events α-particles - travel through space to our planet along with the solar wind affecting its magnetic properties, its energy and its dynamic pressure.

Whenever the solar wind meets certain criteria, the particles result in powerful interactions with the magnetosphere such as storms, sub-storms, radiation belts and other. The most essential of these criteria are:

1. Highly energetic solar wind with velocities above 400km/s
2. Southern oriented interplanetary magnetic field
3. The above must last 1-3 hours in case of sub-storms and more than 5-7 hours in case of storms.

During a storm, energy is transported to the magnetotail of earth's magnetosphere, due to magnetic reconnection. After enough energy has been transported, the magnetotail snaps and ejects the plasma trapped in between the magnetic lines towards the earth. A portion of the ejected plasma goes into orbit around the earth, enforcing the famous ring current, reducing the horizontal component of the magnetic field according to the Dst index. During the recovery phase, the ring current weakens, restoring the magnetic field to its normal values.

The sub-storms are similar dynamic phenomena of smaller scales. The result of these phenomena is the creation of other currents in the magnetosphere and the precipitation of electrons in the atmosphere through the polar cusps. As a result, the spectacular aurora borealis and aurora Australis form. These auroras are visible due to the ionization of the atmospheric particles such as nitrogen and ozone that emit the widely known "greenish light curtains". A difference between the aurora borealis and aurora Australis is that the first is formed in the southern magnetic pole and the other is formed in the northern magnetic pole (opposite to the geographic poles). Another difference between the two auroras is the intensity of their periods due to the inclination of earth's axis to the eclipse plane. During rare events of extremely powerful storms, the auroras can be visible at lower latitudes.

1.3 Particle injection probability

For the purpose of this project, we need to set our focus on the outer radiation belt, in order to calculate and visualize the radiation exposure of commercial flights, which operates in altitudes of 5-12 km. This radiation belt is mostly toroidal and lies in 3-5 Earth radii consisting mostly of electrons with energy of 0.1-10MeV. The magnetic shells that create this belt are connected to high magnetic latitudes on the Earth's surface. Some sample values for quite Sun are:

- L=3 corresponding to latitude $\lambda=67.5^{o}$
- L=4 corresponding to latitude $\lambda=72^{o}$
- L=5 corresponding to latitude $\lambda=78^{o}$

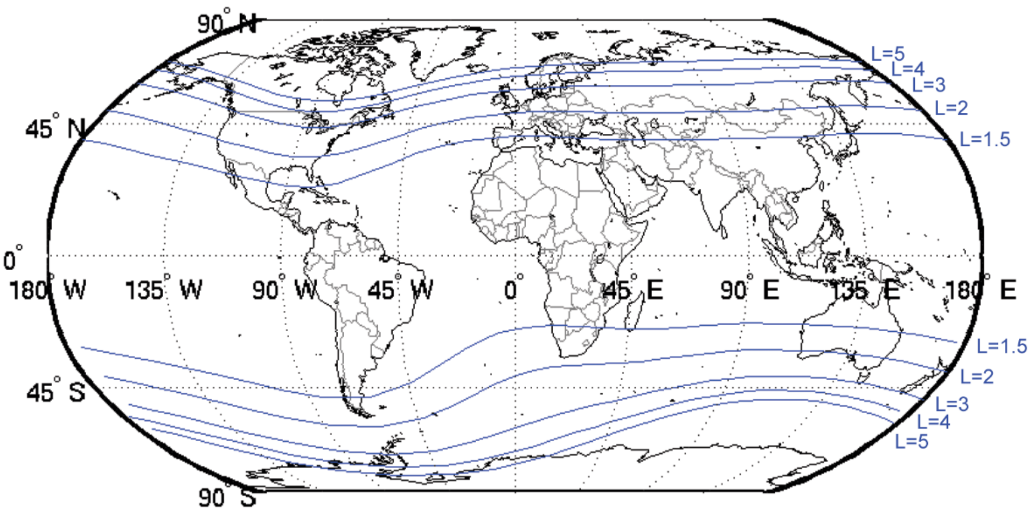

Figure 3. Earth magnetic latitudes and longitudes (© Daniel I Golden)

The electrons of the outer belt move around the magnetic lines through the Larmor effect (gyromotion) preserving the first adiabatic invariant. Simultaneously, they move parallel to magnetic lines, bouncing between two mirror points where the pitch angle becomes 90°. The equation for the pitch angle is given below:

$$\alpha = \arctan\frac{v'}{v} \text{ ,}$$

where v' corresponds to perpendicular component and v corresponds to the parallel (to the magnetic line) component of the velocity.

Moving towards higher latitudes, the pitch angle increases and the particle bounces when α reaches 90°. However, in some cases the pitch angle does not reach the value of 90°. Such cases are:

1. Pitch scattering: the shift of the pitch angle due to interactions with low frequency electromagnetic waves ~ 1Hz
2. Loss cone: when the pitch angle in the equatorial plane is less than critical value which can be calculated by the following equation:

$$\sin^2\alpha_0 = (4L^6 - 3L^5)^{-\frac{1}{2}}$$

As a result, the second adiabatic invariant is not preserved and the particle doesn't bounce, so it falls in the atmosphere through the polar cusps following the magnetic line. The percentage of electrons that actually fall into the atmosphere, are the ones that have a pitch angle lower than the equatorial pitch angle. Assuming that the pitch angle is homogenous among the energy spectrum of electrons, then the percentage that fall into the atmosphere is given by the equation $\alpha<\alpha_0$. The probabilities according to the L are:

- L=3 → Probability=9.3428%
- L=4 → Probability=5.9354%
- L=5 → Probability=4.1963%

These probabilities are one of the factors we used for the calculation of the flux of the electrons falling into the atmosphere.

The GOES satellite is located in geostationary orbit so for the measurements and calculations the probability for L=5 will be used.

1.4 Solar Energetic Particles

Solar energetic particles (SEP) are high-energy particles coming from the Sun. They were first observed in the early 1940s. They consist of protons, electrons and ions with energy ranging from a few tens of KeV to GeV. SEP's can originate either from a solar-flare site or by shock waves associated with coronal mass ejections (CMEs). However, only about 1% of CMEs produce strong SEP events.

Two main mechanisms of acceleration are possible: diffusive shock acceleration or shock-drift mechanism. SEP's can be accelerated to energies of several tens of MeV within 5-10 solar radii (5% of the Sun–Earth distance) and can reach Earth in a few hours. This makes prediction and warning of SEP events quite challenging.

In case of SEP events, highly energetic protons may penetrate into the same magnetic shells and follow the same process resulting in falling into the atmosphere.

2. Our Project

During the project, atmospheric models , a model for the flux of the particles arriving into the atmosphere and finally a model for the absorption of the radiation in it had to be created because all the already existing models were either hard to access or didn't match the project's needs. The created models are described in the following paragraphs.

2.1 Atmospheric model

In the model, the following are assumed:

- Protons with energy less than 1GeV are ignored as stated in paragraph 1.1
- The atmospheric limit is at an altitude of 100km which is a part of the ionosphere where the absorption of particle radiation is considerable.
- The chemical composition is the same along the atmosphere but the density is different
- The flux that arrives at the atmospheric limit is the same as the flux measured with the GOES Satellite.

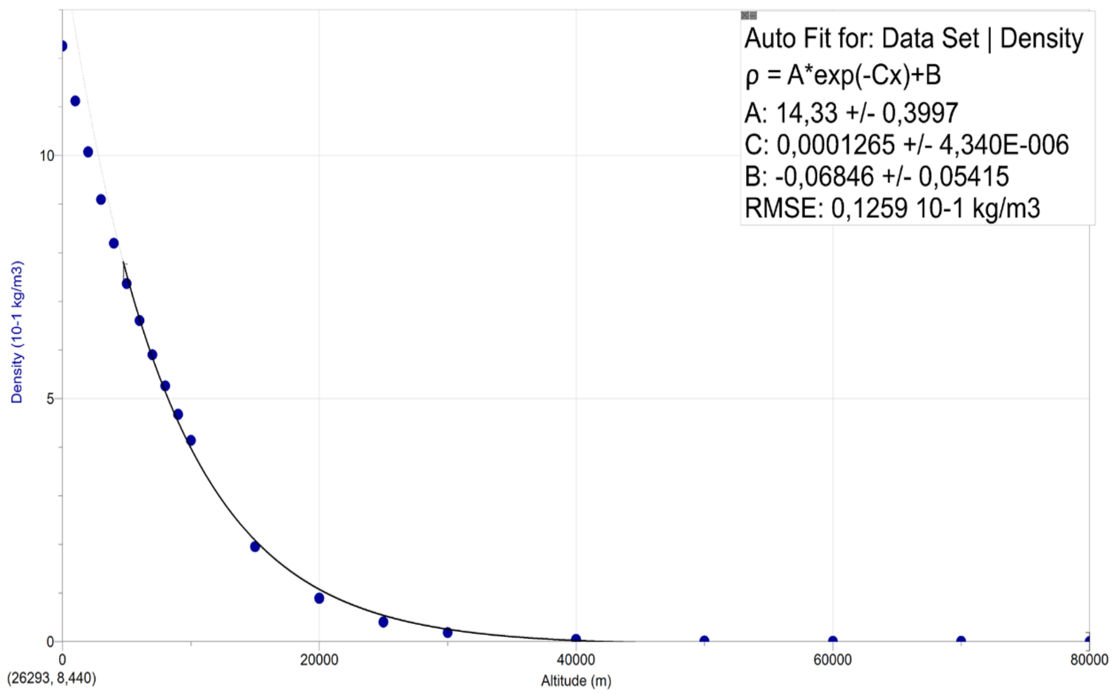

Figure 4. Density-altitude function.

The atmosphere is considered as an ellipsoid where the semi-major axis is the altitude at the equator and the semi-minor axis is the altitude at the poles. For this consideration, the atmospheric limit altitude is linearly proportional to the tropopause limit at the equator and the poles. The atmospheric limit is at 100km for the equator and at 35km for the poles.

The calculations indicate that stopping power is constant in regard to altitude. The stopping power of electrons is shown in the following table.

Chart 1. Stopping Power of electrons calculated for different energies

Energy (MeV)	1,5	3	4
Stopping Power ($\frac{MeV \cdot \mathrm{cm}^2}{gr}$)	1,671	1,783	1,85

Using the stopping power, the energy flux of each particle at the limit of the atmosphere and the atmospheric model, the energy at any altitude can be calculated using the following equation:

$$F=F_O-\frac{S \cdot X \cdot \rho(h)}{\delta\alpha},$$

where F is the energy flux at any altitude, F_0 is the energy flux at the atmospheric limit, S is the Stopping Power, X is the distance to the atmospheric limit, ρ is the atmospheric density, h is the altitude and $\delta\alpha=1cm^2$.

For latest Auroral predictions we used data from NOAA, Space Weather Prediction Center at http://services.swpc.noaa.gov/text/aurora-nowcast-map.txt through the website http://www.swpc.noaa.gov/products/aurora-30-minute-forecast.

As for the meteorological phenomena, they take place beneath the flight height and as a result they don't influence the radiation the airplanes receive. Despite of that, increases and reductions of air density do happen in those hights due to air currents.

As for the meteorological phenomena, they take place beneath the flight altitude so they do not need to be included in the model. In spite of that, increases and reductions of the air density do happen in those hights due to air currents and such currents will be added in the future.

2.2 Calculations

The full calculation code is given in the link:

https://github.com/ax3l91/space-apps-2017-mayday-athens/blob/master/Kp.ipynb.

It takes into consideration all the factors explained in the project. As input, it takes the Kp index, flight routes, GOES Satellite flux data, aurora prediction data (just for display). It simulates the flight route and the radiation effects that are encountered and outputs the total radiation dose for an average human, the time series of exposure during the flight, physical simulation in 3D world model.

Under construction is an algorithm to optimize the flight path in order to minimize the total radiation dose proportionally to flight distance. ***The algorithm is ready but there was not available enough time and computational power to generate results. ***

2.3 Visualization

The full visualization code is given in the link:

https://github.com/ax3l91/space-apps-2017-mayday-athens/blob/master/Kp.ipynb

Besides the visualization given at Kp.ipynb, the browser provides a front end that pulls the simulation data and visualizes them in user friendly form.

The visualization is split in four parts.

1. 3D visualization of the globe with the simulated flight path pseudo-colored, according to the radiation intensity at each point.
2. 2D visualization of the world map marking the flight path and showing the expected aurora probability at each point.
3. Live chart of the cumulative radiation dose of the flight path to the distance traveled. The user can hover over the line of the chart to get exact values of time and total radiation dose value for a point in time.
4. Total radiation dosage and generated comments on the health aspects of the simulated flight in an understandable way for the general public, with examples out of the everyday life.

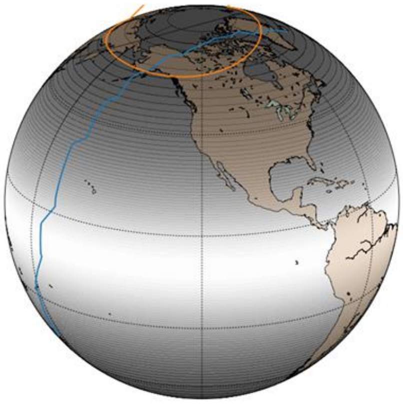

Figure 5. Depiction of flight path (blue line), the lowest limit in which solar radiation is taken into account (orange circle), radiation dose globally (grey)

3. Biological consequences

Firstly, almost 99% of the mass of the human body is made up of six elements: oxygen(O_2), carbon(C), hydrogen(H), nitrogen(N), calcium(Ca), and phosphorus(P). Only about 0,85% is composed of another five elements: potassium, sulfur, sodium, chlorine, and magnesium. All eleven are necessary for life.

The radiolysis of water due to ionizing radiation, results in the production of electrons, H atoms, OH radicals, HO^+ ions and molecules (dihydrogen H_2 and hydrogen peroxide H_2O_2). Radiolysis is an indirect way of energy transfer into biomolecules. The products of radiolysis, free radicals such as H_2O_2 on high concentrations are toxic for the cells because they have the ability to oxidize organic compounds. Some research connects the existence of free radicals with premature aging, cancer, respiratory problems, even failure at ATP production from mitochondria. If a big number of cells drive into apoptosis or necrosis then we have organ failure and finally death.

The direct way of energy transfer can cause physical and chemical changes in proteins, lipids and DNA. The cell is “armored” with specialized repair mechanisms and they can repair that change. However, sometimes they aren’t available to repair the damages and finally the cell continues to live with the damages (the beginning of cancer issues) or dies(apoptosis).

The severity of the molecular damage caused is directly related to the degree of ionization produced by the radiation in the biological tissue, i.e., by the rate at which radiation radiates its energy. A relative magnitude that quantifies the energy deposit rate is Linear Energy Transfer (LET) defined as the energy transfer rate in a particular area of matter.

$$LET = \frac{dE(absor.)}{dx}\left(\frac{KeV}{\mu m}\right)$$

→ The increase of LET value implies more biological damage.

Stopping power for human body

The Stopping power for the human body was calculated using the same method. The chemical components used in the application are:

Chart 2. Components of human body and percentage in human body

Chemical Component	Oxygen	Carbon	Hydrogen	Nitrogen	Calcium	Polonium
Percentage (%)	0.65	0.185	0.095	0.032	0.015	0.01

For each energy spectrum, the stopping power is shown in the following diagrams.

- Electrons

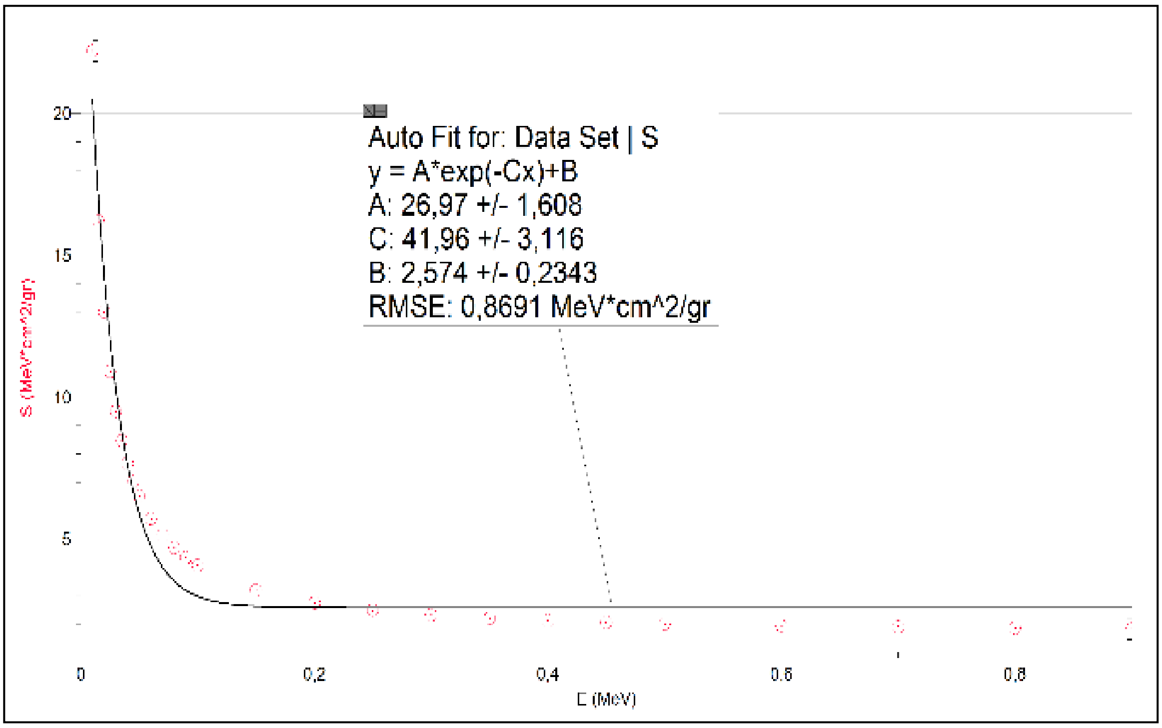

Figure 6. Stopping power of electrons with E<1MeV.

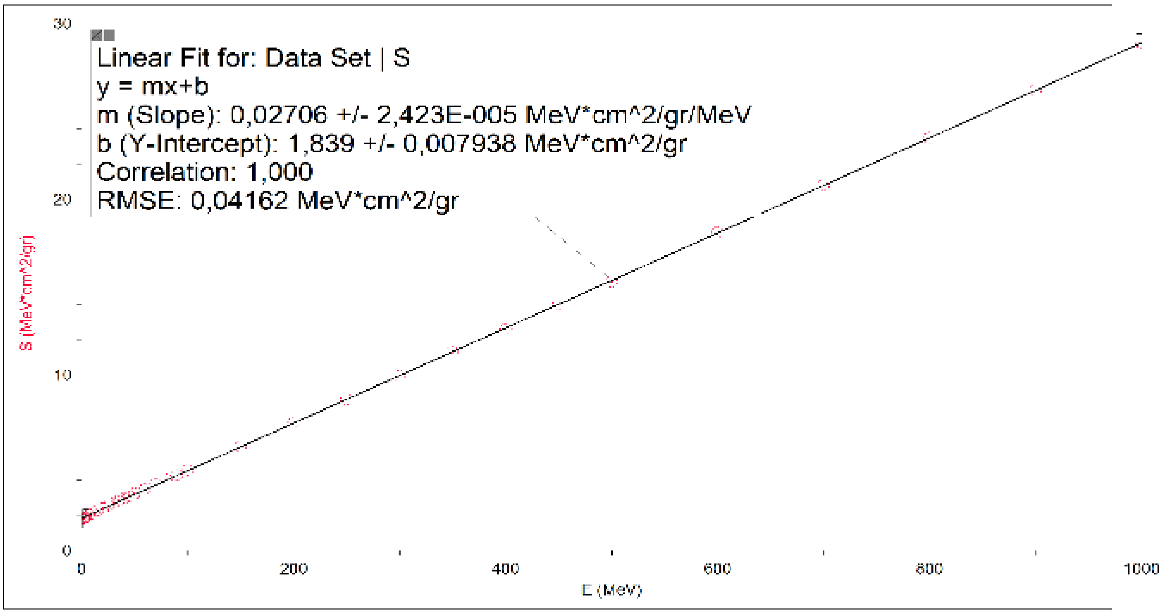

Figure 7. Stopping power of electrons with E≥1 MeV.

- Protons

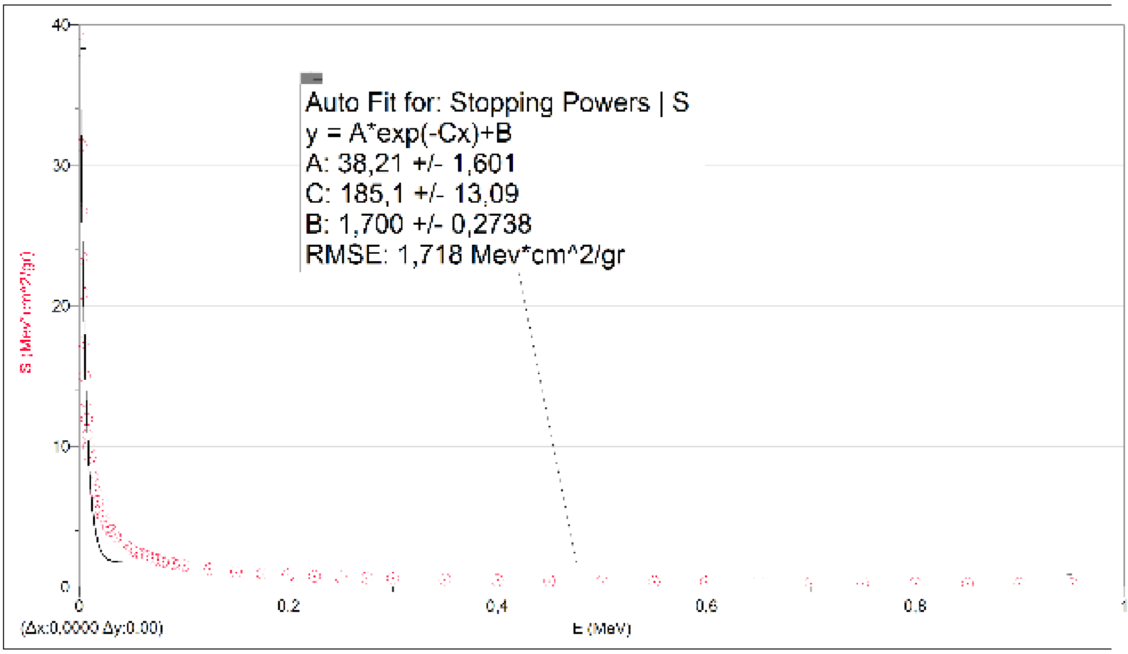

Figure 8. Stopping power of protons with E<1MeV.

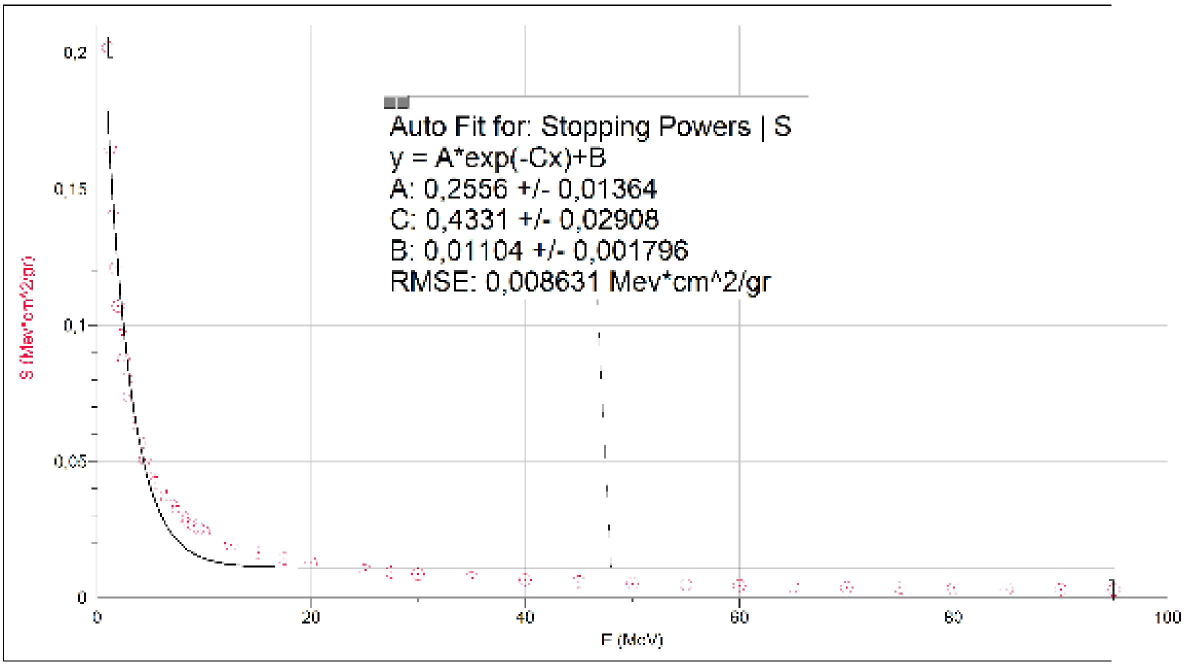

Figure 9. Stopping power of protons with 1≤E<100 MeV.

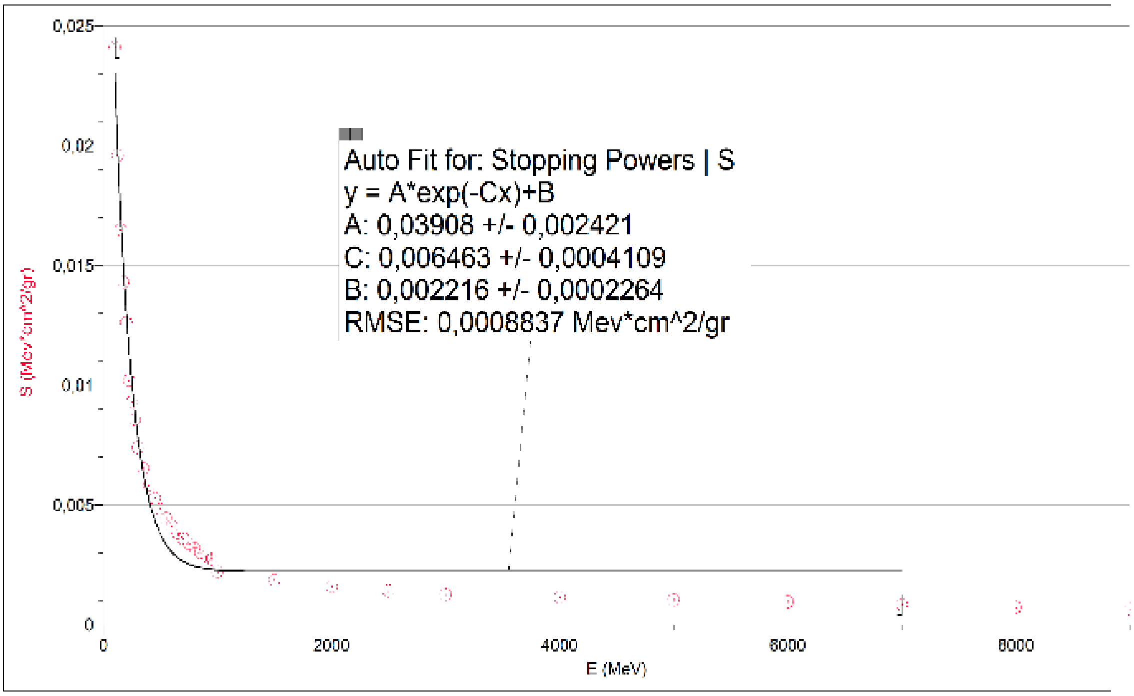

Figure 10. Stopping power of protons with E≥100MeV.

Using the stopping power for human body and flux at the flight altitude, it is now possible to calculate the effective dose using the radiation dosimetry equation

$$D = K\int_{\Omega}\int_{0}^{\infty} S_j(E)\Phi_j(x,\Omega,E)d\Omega dE = \int_{L} Q(L)D_j(x,L)dL\; E(x) = \sum_T\sum_j w_T H_{j,T}(x),$$

where D is the energy deposited in a target medium by the radiation field of particle j, which is the dose. In the above equation, $S_j(E)$ is the target stopping power for particle j ($MeV/g/cm^2$) and K is a unit conversion factor (1.602x10−10).

Dose equivalent in tissue T from particle j (H_j,T(x)) is defined in terms of the tissue LET dependent quality factor Q, such that

$$H_{j,T}(x) = \int_L \; Q(L) D_j(x, L) dL,$$

where L is LET, which can be approximated by the stopping power in units of KeV/um; $D_j(x,L)$ is the spectral dose distribution from particle j in terms of LET, and Q(L) is the tissue LET-dependent quality factor.

The relationship between the probability of biological damage and dose equivalent is found to be also depended of the organ or tissue irradiated. A further dosimetric quantity, called the effective dose, is defined to include the relative contributions of each organ (w_T) or tissue to the total biological detriment caused by radiation exposure. The effective dose E(x) is the sum of weighted dose equivalents in all the organs and tissues in the human body, such that

$$E(x) = \sum_T \sum_j w_T H_{j,T}(x)$$

Also, during a flight there are some exposure variables that we have to consider such as the time of exposure during an air flight, the age and the health background of each pilot and a possible pregnancy.

The side effects of exposure in radiation, variate accordingly the exposure variables. Aircrew is exposed to low-level cosmic ionizing radiation. Annual effective doses for flight crew have been estimated to be in the order of 2-5mSv and can attain 75mSv at career end. The last 15–20 years, epidemiological studies usually focus on radiation-associated cancer. These studies are summarized that the overall cancer risk was not elevated in most studies and subpopulations analyzed, while malignant melanoma, other skin cancers and breast cancer in female aircrew have shown elevated incidence, with less risk elevations in terms of mortality. In some studies brain cancer risk appears elevated. Cardiovascular mortality risks were generally very low.

If we have a near-polar or polar flight the possibility for the air crew to have serious cancer problems is very low. A pilot during the flight can receive electrons with energy 0.1-1 MeV and rarely (according to the above) protons and neutrons with 1 GeV energy. After calculations, the range of electrons with energy 1 MeV in human tissues is about and the skin with subcutaneous tissue thickness for an average human is 9.96mm. Consequently, the particles will stop inside the layer of the skin and maybe this is the reason for skin and breast cancer issues.

4. Radiation Protection and Aircraft Shielding

The amount of dose of radiation received while flying, depends on the duration of the flight, the altitude, the latitude and of course the solar activity. Lowest dose rates at a given altitude are found near the equator and at short time flights, and increases at long time flights and approaching the poles (higher altitude leads to higher dose rate). Passengers and crew members in order to reduce exposure to cosmic radiation should avoid long flights, flights at high latitudes or near-pole flights. Avoiding exposure to solar particle events is difficult, because we usually cannot have quick and valid predictions.

Investigations have been made in order to find appropriate materials for the aircraft. The first material, which contains a large amount of hydrogen and thereby, guarantees an efficient slow down and energy loss of very fast neutrons by means of elastic collisions, a process called thermalization. Its efficiency relies on the fact that neutrons have nearly the same mass as hydrogen nuclei (protons) and as a result in each collision a maximum of their kinetic energy is transferred to the hydrogen nuclei. The second constituent of the shielding solution is characterized by a high ability to absorb slow, thermal neutrons such as boron or compounds.

When it comes to the first shielding component required to attenuate highly energetic neutrons, one natural way would be to use liquid with cryoplane technology. LH2 is a material that provides a long-term technological option as alternative fuel. It must be cooled down to the liquid state and thus necessitates very good insulation of the tanks or pipes. For this reason, new aircraft configurations are required.

Candidate materials for neutron protection include composite materials with a polymeric phase, featuring neutron-absorbing particle inclusions, traditionally of micrometer size. However, it has been shown that better shielding requires nanometer range. Such nano-composites could be applied as millimeter-thin films, foams or pastes to the ceiling of an aircraft's cabin interior.

5.Future goals

- Take into consideration improved models of GCR and SEPs.
- Include a more detailed model of magnetosphere dynamics.
- Improve the code to take into consideration magnetic anomalies of the earth's magnetic field like the South Atlantic Anomaly.
- Calculate the cutoff rigidity to improve the total energy flux of particles and total dose.
- Improve the created atmospheric model to take into consideration atmospheric weather phenomena and conditions at flight altitudes.
- Use existing models of hadronic shower to further improve the total energy flux at flight altitude.
- Make a detailed shielding model to protect crew members and passengers from the radiation exposure.
- Make a full web application allowing the user to choose a flight of his own, existing or not (Dynamic flight selection).
- Improve code to optimize any flight path to minimize the radiation dose proportionally to flight distance.

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