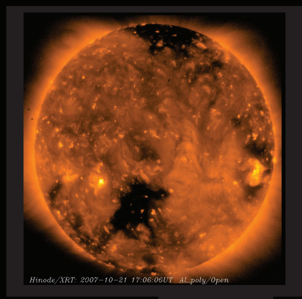
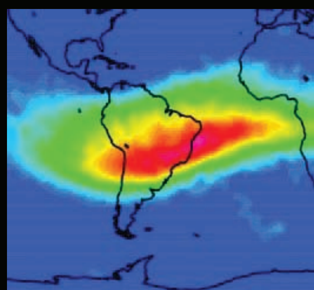
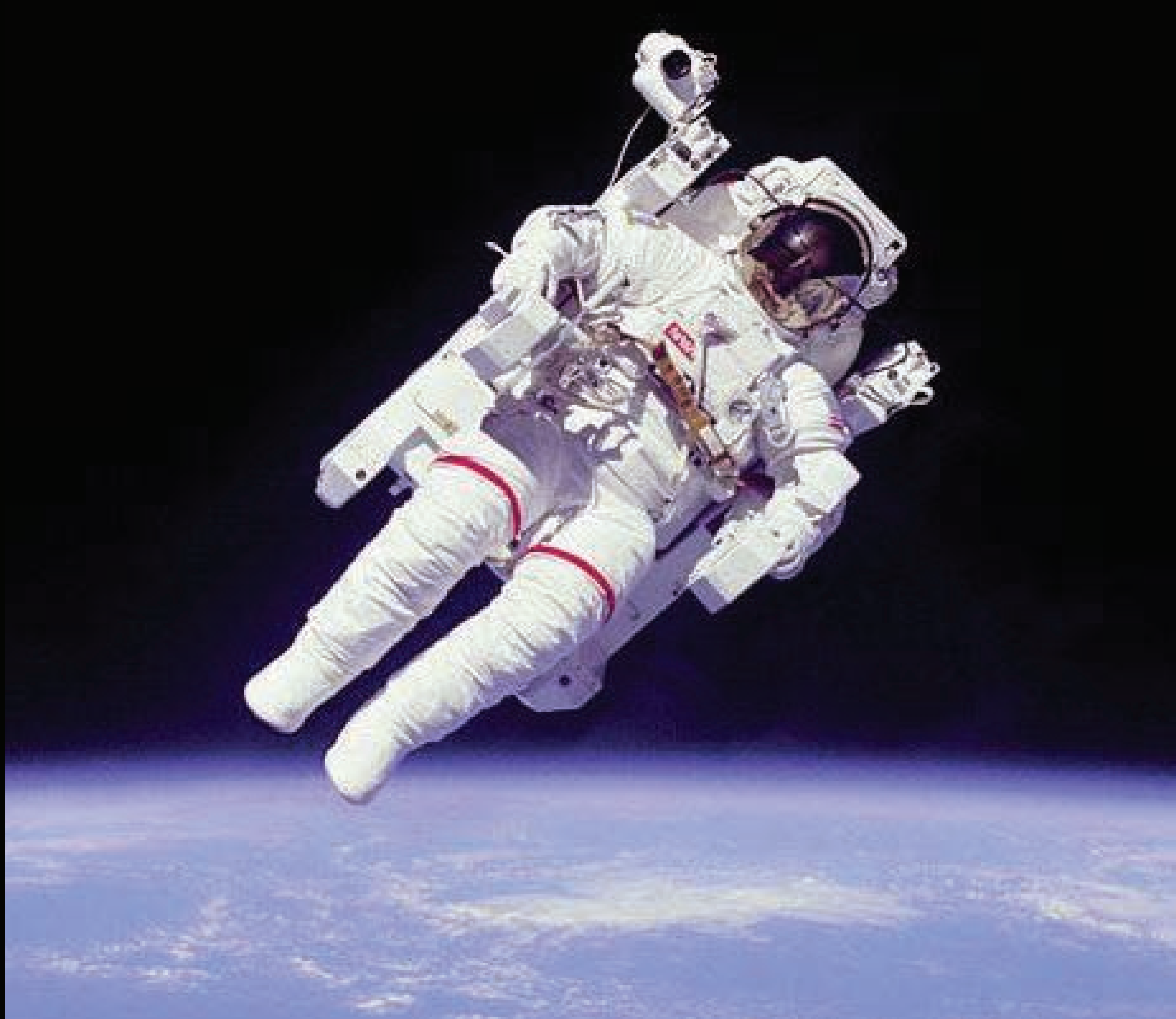
National Aeronautics and Space Administration

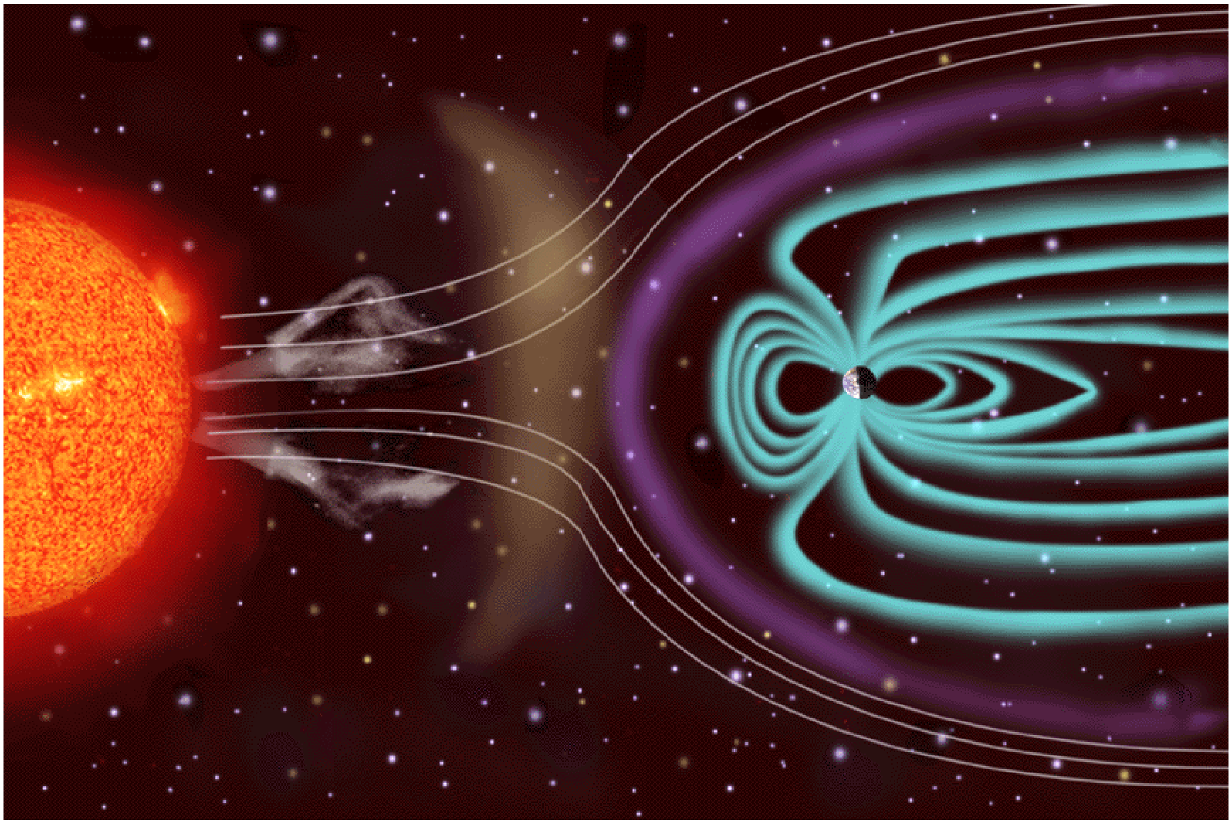




Radiation Math



Radiation Math



Mathematical problems featuring radiation effects applications

(Updated Version, July 2011)

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and

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This collection of activities is based on a weekly series of space science problems distributed to thousands of teachers during the 2004-2011 school year. They were intended for students looking for additional challenges in the math and physical science curriculum in grades 7 through 12. The problems were created to be authentic glimpses of modern science and engineering issues, often involving actual research data. The problems were designed to be 'one-pagers' with a Teacher's Guide and Answer Key as a second page. This compact form was deemed very popular by participating teachers.

The topic for this collection is **Radiation** which tends to be a very mysterious subject among students and adults. It shouldn't be. Living on the surface of Earth, we are bathed in a natural background of radiation from many sources. Usually the term is identified by the harmful sources (nuclear bombs and power plants), and health risks that occur when too much radiation is absorbed, such as from skin cancer and UV over-exposure, or medical X-rays, CAT scans and cancer therapy. This book will make the student familiar with the many forms of radiation, how it is measured, and what different doses can lead to over time.

Acknowledgments:

Ms. Geyer is an Education Specialist for the Virginia Space Grant Consortium (VSGC) in Hampton, Virginia. She supports two NASA programs, NASA's Global Climate Change Education project and Virginia Aerospace Science and Technology Scholars Program. Geyer holds a Bachelor of Science degree from the College of New Jersey in Physics and a Master of Science degree from University of Massachusetts at Lowell in Radiological Sciences and Protection. Prior to joining VSGC she was a classroom teacher for 13 years, teaching AP Physics and Earth Science and was a civil servant for 5 years as a Radiation Physicist for the Nuclear Regulatory Commission and the US Navy

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Alignment with Standards

AAAS Project:2061 Benchmarks

(9-12) - Mathematical modeling aids in technological design by simulating how a proposed system might behave. 2B/H1 ---- Mathematics provides a precise language to describe objects and events and the relationships among them. In addition, mathematics provides tools for solving problems, analyzing data, and making logical arguments. 2B/H3 ----- Much of the work of mathematicians involves a modeling cycle, consisting of three steps: (1) using abstractions to represent things or ideas, (2) manipulating the abstractions according to some logical rules, and (3) checking how well the results match the original things or ideas. The actual thinking need not follow this order. 2C/H2

NCTM:"Principles and Standards for School Mathematics"

Grades 6–8 :

- work flexibly with fractions, decimals, and percents to solve problems;
- understand and use ratios and proportions to represent quantitative relationships;
- develop an understanding of large numbers and recognize and appropriately use exponential, scientific, and calculator notation; .
- understand the meaning and effects of arithmetic operations with fractions, decimals, and integers;
- develop, analyze, and explain methods for solving problems involving proportions, such as scaling and finding equivalent ratios.
- represent, analyze, and generalize a variety of patterns with tables, graphs, words, and, when possible, symbolic rules;
- model and solve contextualized problems using various representations, such as graphs, tables, and equations.
- use graphs to analyze the nature of changes in quantities in linear relationships.
- understand both metric and customary systems of measurement;
- understand relationships among units and convert from one unit to another within the same system;

Grades 9–12 :

- judge the reasonableness of numerical computations and their results.
- generalize patterns using explicitly defined and recursively defined functions;
- analyze functions of one variable by investigating rates of change, intercepts, zeros, asymptotes, and local and global behavior;
- understand and compare the properties of classes of functions, including exponential, polynomial, rational, logarithmic, and periodic functions;
- draw reasonable conclusions about a situation being modeled.

Mathematics Topic Matrix

Topic	Problem Numbers																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Inquiry																															
Technology, rulers																															
Numbers, patterns, percentages							X										X														
Averages																															
Time, distance,speed								X																							
Areas and volumes	X	X							X					X					x												x
Mass, density, volume																		x		x											
Scale drawings																															
Geometry																			x												
Scientific Notation	X	X																X	x	x											
Unit Conversions	X	X	X	X	X	X	X	X	X												x	x									
Fractions																															
Graph or Table Analysis									X		X				X	X	X	X						x	x	x	x	x	x	x	
Solving for X												X	X																		
Evaluating Fns																			x												
Modeling											X				X														x		
Probability										X																					
Rates/Slopes	X	X	X	X	X	X	X	X	X	X	X			X	X	X					x	x	x	x	x	x	x	x	x	x	x
Logarithmic Fns											X	X	X		X											x					
Exponential Fns												X	X																		
Polynomials																															
Power Fns											X																				
Conics																															
Piecewise Fns																															
Trigonometry																															
Integration																															
Differentiation																															
Limits																															

Mathematics Topic Matrix

Topic	Problem Numbers																			
	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Inquiry																				
Technology, rulers																				
Numbers, patterns, percentages	X							X												
Averages									X	X	X	X		X	X		X	X		
Time, distance,speed												X	X							
Areas and volumes					X															
Scale drawings																				
Geometry					X															
Scientific Notation																				
Unit Conversions																				
Fractions																				
Graph or Table Analysis		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Solving for X																				
Evaluating Fns																				
Modeling																				
Probability														X	X					X
Rates/Slopes						X	X													
Logarithmic Fns						X														
Exponential Fns				X																
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Differentiation																				
Limits																				

How to Use this Resource

Teachers continue to look for ways to make math meaningful by providing students with problems and examples demonstrating its applications in everyday life. Space Mathematics offers math applications through one of the strongest motivators-Space. Technology makes it possible for students to *experience* the value of math, instead of just reading about it. Technology is essential to mathematics and science for such purposes as “access to outer space and other remote locations, sample collection and treatment, measurement, data collection and storage, computation, and communication of information.” 3A/M2 authentic assessment tools and examples. The NCTM standards include the statement that "Similarity also can be related to such real-world contexts as photographs, models, projections of pictures."

Radiation Math is designed to be used as a supplement for teaching mathematical topics. The problems can be used to enhance understanding of the mathematical concept, or as a good assessment of student mastery.

Radiation Math can be used as a classroom challenge activity, assessment tool, enrichment activity or in a more dynamic method as is explained in the above scenario. It is completely up to the teacher, their preference and allotted time. What it does provide, regardless of how it is used in the classroom, is the need to be proficient in math. It is needed especially in our world of advancing technology and physical science.

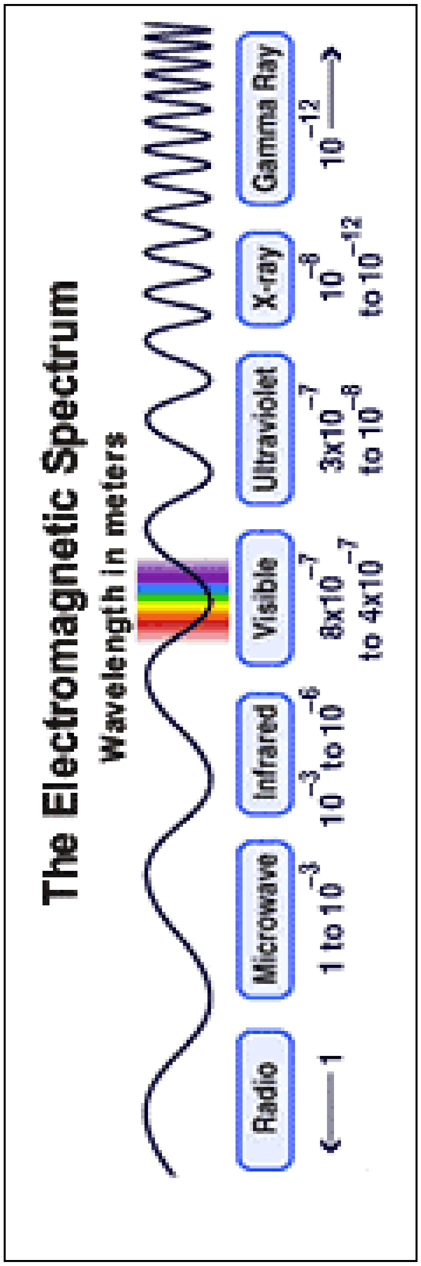
An integrated classroom technique provides a challenge in math and science classrooms, through a more intricate method for using **Radiation Math**. Read the scenario that follows:

Mr. Smith was questioned by a group of students about the amount of radiation that they absorbed in their bodies to cause some dangerous health issues. Mr. Smith offered the students an *After School Enrichment* opportunity using Radiation Math as the source for students to become familiar with the forms of radiation, how it is measure, and what different doses can lead to over time. Mr. Smith identified that some of his high school students would find some of the mathematical concepts difficult, this gave him a chance to group students with advanced math skills with students having less knowledge to work together, sharing their own abilities with other students. Mr. Smith saw an increase in math interest as students identified the need for using advanced math skills. The students elected to continue their own research using the knowledge they gained developing a presentation to share with parents and other students, Mysterious Radiation-Knowledge Can Save a Life.

An Introduction to Radiation

Believe it or not, you are surrounded by radiation! As you are sitting here reading this article, electromagnetic radiation from sunlight, electric lights, power cables in the walls, and the local radio station are coursing through your body. Radiation is a catch-all word that is popularly applied to all sorts of natural phenomena, and since the 1950's remains a very scary word to most adults. Is radiation something to worry about?

As for many foods, it all depends on how much you absorb, and in what forms!



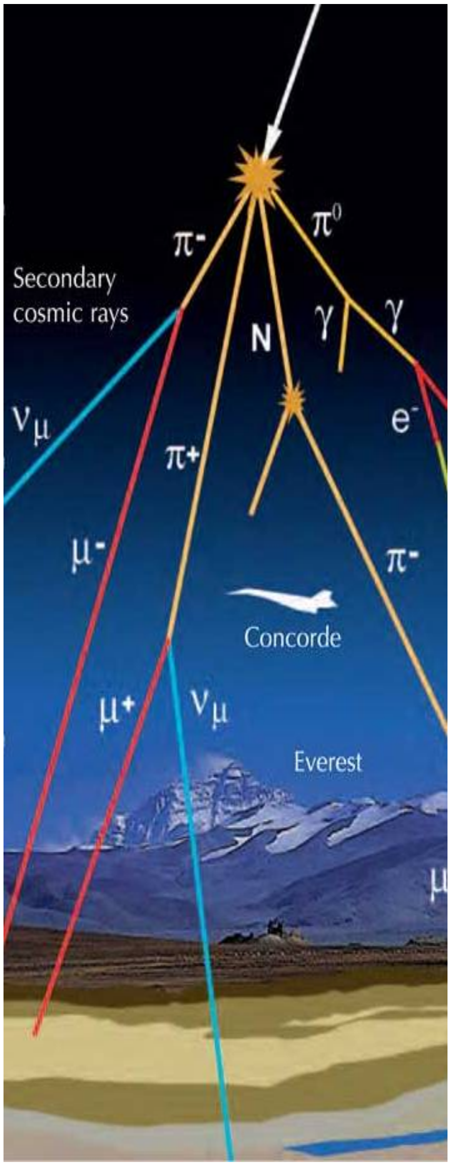
There are two main types of radiation: **electromagnetic** radiation, and **particle** radiation. Both forms carry energy, which means that if you accumulate too much over time, either in the tissues of your body, or in sensitive electronic equipment, they can potentially do damage.

Electromagnetic Radiation

Also called 'EM radiation', it travels at the speed of light, and is defined by its wavelength or its frequency. EM radiation spans a wide wavelength range from gamma-rays and X-rays at the shortest, through ultraviolet and visible light, and to longer wavelengths in the infrared, and radio. The harmfulness of EM radiation depends on BOTH its intensity and its wavelength.

A small amount of short-wavelength (UV-B) ultraviolet radiation can give you a nice tan, and allows your skin to form Vitamin-D. Too much can increase your risk for skin cancer. Even too much radio energy can be harmful (think of your microwave oven!).

EM radiation is produced by heated bodies, chemical reactions, nuclear reactions and a variety of man-made technologies such as medical imaging systems, radio transmitters, electrical power systems, cell phones, microwave ovens and computers.



Cosmic Rays are very high-energy particles including protons, neutrons, electrons and some atomic nuclei produced by astronomical objects such as the sun, supernovae or distant galaxies. When entering Earth's atmosphere, they produce: Cosmic ray air showers, which are common sources of particle radiation near Earth's surface, include nuclear particles (pions and muons) and gamma-rays produced during collisions with oxygen and nitrogen nuclei in the atmosphere.

(Image courtesy Alberto Izquierdo and Francisco Barradas Solas, Science in School, http://www.scienceinschool.org/print/1163)

Particle Radiation

This radiation consists of particles of matter traveling through space at high-speed, but never faster than the speed of light (299,792 km/s). Usually these particles are sub-atomic such as electrons, neutrons, alpha particles, or even entire atoms with some of their electrons removed (ions).

Particle radiation is usually produced by unstable atoms that are 'radioactive', or by many different astronomical systems in which matter can be accelerated to high speed such as supernova explosions, pulsars and solar flares.

There are three common types of particle radiation found on Earth, and produced by many radioactive substances. Each produces its own level of tissue damage.

Alpha-particles are given-off by radioactive atoms. They are nuclei containing two protons and two neutrons: essentially helium nuclei. They can be stopped by a sheet of paper and rendered harmless, however they can be trapped on dust particles and be inhaled, doing damage to lung tissue as they build up their concentration. Spacesuits can typically shield an astronaut from alpha-particles that occur in solar flares and cosmic rays.

Beta-particles (or Beta-rays) are also given off by radioactive atoms during the process of 'beta decay'. They consist of energetic electrons traveling at high-speed, and require several millimeters of aluminum to stop most of them. A spacesuit normally has a few millimeters of aluminum in its fabric, so astronauts are usually well-protected from beta-rays from solar flares and other sources.

Neutron particles are produced in nuclear reactions including fission and fusion. Because they carry no charge, they easily penetrate many substances. Large quantities of water or cement are required to shield against neutron radiation. The walls of spacecraft provide adequate shielding from neutron particles. During EVAs, astronauts receive unavoidable radiation exposure to neutrons and other energetic particles such as cosmic rays.

Dose and Dose Equivalent

Scientists measure radiation doses and dose equivalent in terms of units called Rads and Rems (Grays and Seiverts are used in Europe in the SI System).

Dose: This is a measure of the amount of total energy that is absorbed by matter over a period of time. This matter can be human tissue, or sensitive computer circuitry. The unit for dose is the Rad, which means 'Radiation Absorbed Dose'. One Rad is equal to 100 ergs of energy delivered to one gram of matter. The equivalent SI unit is the Gray (G). **One Gray equals 100 Rads.**

Dose Equivalent: This compares the amount of absorbed energy (Rads) to the amount of tissue damage it produces in a human. It is measured in units of the Rem, which means 'Roentgen Equivalent Man'. The equivalent SI unit is the Seivert (Sv**). One Seivert equals 100 Rems.**

Radiation dose can be very accurately measured and defined. It is just the amount of energy delivered to a sample of matter. Equivalent dose, however, is much more complicated. This term has to do with the amount of **damage** that a given amount of energy does to a tissue sample or an electronic component. Each kind of radiation, for the same exposure level, produces a different amount of damage. Mathematically, this is represented by the equation:

Dose Equivalent (in Rem) = Dose (in Rads) x Q

Different forms of radiation produce different levels of tissue damage. EM radiation, such as x-rays and gamma-rays, produce 'one unit' of tissue damage, so for this kind of radiation Q = 1, and so 1 Rad = 1 Rem. This is also the case for beta radiation, which has the same Q value. For alpha particles, Q = 15-20, and for neutrons, Q = 10. That means that a dose of 1 Rad of radiation (which equals 100 ergs delivered to 1 gram of matter) produces a dosage of 10 Rem for Q = 10.

Radiation also has different effects depending on how much you absorb over different amounts of time, and different areas of the body involved. Let's consider some extreme examples where part olf all of the body is irradiated with a big dose over a short time, or a small dose over a long time.

Strong and Brief!

Example 1: Big dose over a short time, over small area.

In cancer therapy, small parts of your body are irradiated to kill cancerous cells. This works because radiation transports energy into cellular tissue where it is absorbed, and cancerous cells are very sensitive to heat compared to normal cells. Although patients sometimes report nausea and loss of hair, the benefits in destroying cancerous cells (the survival of the patient) far outweighs the collateral effects, which are usually temporary. Typical dosages are about 200 Rads delivered over a period of about an hour, and over a few square centimeters. Higher doses of 5,000 Rads are also used, but delivered over a number of separate 1-hour sessions to build up the dose to a single tumor area!

Example 2: Big dose over a short time, over large area.

For whole-body doses, delivered over an hour or less, the effects are far worse as the table below shows! (Note: 100 Rem = 1 Sievert)

50 - 100 Rem	No significant illness
100 - 200 Rem	Nausia, vomiting. 10% fatal in 30 days.
200 - 300 Rem	Vomiting. 35% fatal in 30 days.
300 - 400 Rem	Vomiting, diarrhea. 50% fatal in 30 days.
400 - 500 Rem	Hair loss, fever, hemorrhaging in 3wks.
500 - 600 Rem	Internal bleeding. 60% die in 30 days.
600 -1,000 Rem	Intestinal damage. 100% lethal in 14 days.
5,000 Rem	Delerium, Coma: 100% fatal in 7 days.
8,000 Rem	Coma in seconds. Death in an hour.
10,000 Rem	Instant death.

Weak and Long! On the ground, you receive about 0.4 Rem each year (e.g. 400 milliRem/yr for Q=1) from: natural backround radiation; radiation from all forms of medical testing; what you eat; and where you live. Over the course of your lifetime, say 80 years, this adds up to 32 Rems of radiation. By far, the biggest contribution comes from radioactive radon gas in your home, which can amount to as much as 0.1 Rem/year, and yields a lifetime exposure of 8 Rems. Some portion of this radiation exposure invariably contributes to the average cancer risk that each and every one of us experiences.

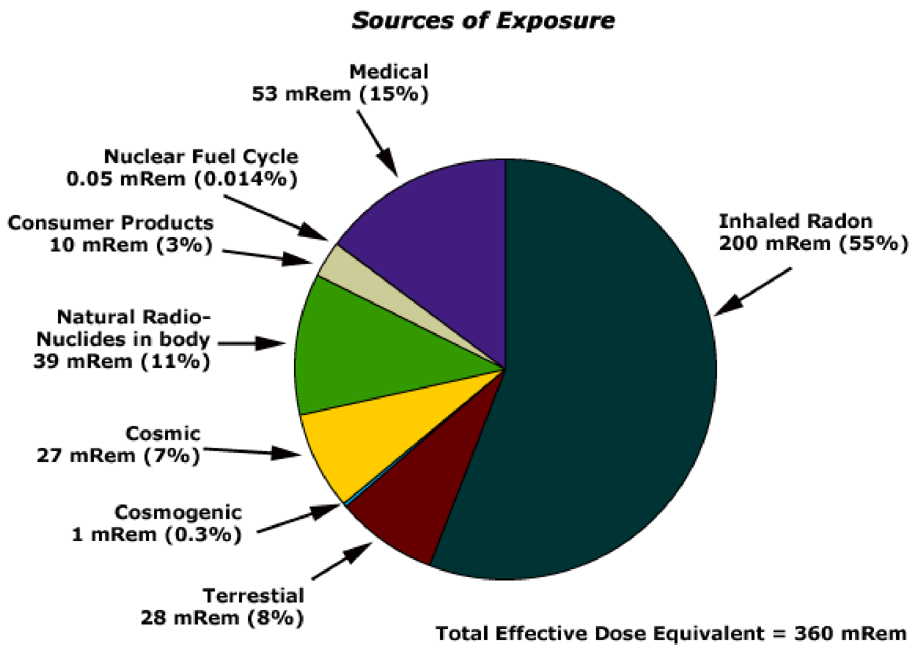
Medical Diagnostic Radiation (Q=1 for EM):

0.002 Rems	Dental x-ray
0.010 Rems	Diagnostic chest X-ray
0.065 Rems	Pelvis/Hip x-ray
0.150 Rems	Barium enema for colonoscopy
0.300 Rems	Mammogram
0.440 Rems	Bone scan
2 to 10 Rems	CT scan of whole body

So, the medical impact of radiation depends on the intensity of the dose, whether your whole body or just a few cells are involved, and how long your body will be exposed to a given dose. This makes the calculation of radiation effects a complicated process. 280 Rems all at once is fatal for 35% of people after 30 days, but the same exposure over a 70-year lifespan is only 4 Rems each year, which is easily survivable and harmless.

Just remember that some exposure to radiation is simply part of the price we pay for living on the surface of Earth and eating a well-balanced diet. In fact, because radiation leads to mutations, and mutations lead to evolution, it is entirely reasonable to say that, without radiation, the evolution of organic life on this planet would have taken a very different, and probably much slower, path!

Natural and Artificial Radiation Sources



This figure shows the various kinds of radiation sources that contribute to your annual dose. Some of these sources you can do nothing about:

Natural Radionuclides in Body refers to the radioactive elements out of which your bones and tissues are constructed. Potassium is a naturally radioactive element. A typical human body contains 150 grams of potassium, which produces most of our body's radioactivity!

Nuclear Fuel Cycle refers to atmospheric forms of radioactivity that are there because of nuclear power plants. Coal miners are also exposed to high doses of radioactive coal dust!

Medical refers to annual dental x-rays or nuclear imaging. If you have cancer and undergoing radiotherapy, you are exposed to even more radiation.

Cosmic refers to sources of radiation in the form of cosmic rays that come from the sun or from space. If you live at higher elevations or are a frequent airline passenger, this exposure can be higher.

Terrestrial refers to sources of radiation in soils or rocks. The clay in some areas contains higher concentrations of radioisotopes than in other locations. Granite has large quantities of uranium or other radioactive ores embedded in the rock.

Consumer Products can include food. Bananas are rich in potassium, but also contain slight quantities of the radioactive isotope of potassium.

Radon Gas that can be trapped in your basement, and is a major source of lung cancer. To greatly lower your lung cancer risk, keep your basement ventilated, and periodically checked for radon!

Radioactive Contamination versus Radiation Exposure

Radioactive contamination is any material that gives off radiation (energy in the form of alpha particles, beta particles, or gamma rays) in a location where it is not desired. For example, in the aftermath of the Japan Earthquake of March 10, 2011, stored spent fuel rods of the Fukushima nuclear plant became part of a fire. The radioactive material contained in the rods was released to the environment through ash and smoke. The ash is considered to be radioactive contamination and any object or place that it lands on is considered to be contaminated. In contrast, properly stored spent fuel rods are **not** considered to be contamination because the radioactive material is contained in the desired location and unable to spread.

Anytime that radioactive material is not in a sealed radioactive source container and might be spread onto other objects, radioactive contamination is a possibility. A person near the Fukushima Nuclear plant in Japan could become externally contaminated if contaminated ash falls on their clothing or skin. A contaminated person will be exposed to the radiation (energy in the form of alpha particles, beta particles, or gamma rays) emitted by the radioactive materials in the ash until the ash is removed. Decontamination methods include proper disposal of the clothing and washing of the skin. Internal contamination is also a possibility if the contaminated ash is breathed in or swallowed. Risk of internal contamination can be reduced by wearing a mask or placing a wet towel over the nose and mouth preventing the entry of the ash into the body. Detection of contamination is usually accomplished by passing the wand of a radiation detector close to and over the surface areas that are suspect.

Radiation exposure on the other hand, is not spread and doesn't get "in" or "on" people. People become exposed to radiation when alpha particles, beta particles, or gamma rays hit their body and deposit energy in their body. That energy may or may not go on to cause biological harm. A person becomes exposed to radiation as the radiation eminates from a nearby radioactive source. Exposure to radiation can be minimized by reducing the time spent near the source of radiation, by getting further away from that source or by placing sufficient shielding between the person and the source. The source could be radioactive contamination that is on them, or near them, or it could come from a nearby stored and secure source of radiation.

For example, in the aftermath of the Japan Earthquake of March 10, 2011, workers working near the spent fuel storage areas of the Fukushima nuclear plants were normally exposed to very low levels of radiation that were deemed acceptable. Then damage resulting from the earthquake and Tsunami caused water covering the spent fuel to be lost. That water helped to shield the spent fuel and keep the radiation exposures to workers low. With the water missing, exposure rates increased, and workers had to evacuate those areas in order to decrease the time spent near the radiation source, and increase the distance from the radiation source, thereby reducing their exposure.

Exposure levels are measured with hand held meters that measure ambient radiation levels, and with thermoluminescent dosimeters that are worn by people working near radiation sources to monitor their exposure rates and ensure that they are below acceptable standards.

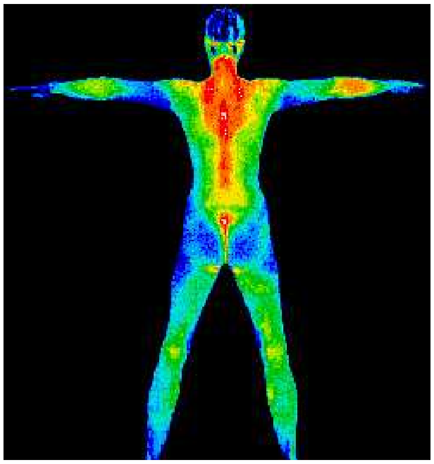


Image of a human emitting infrared 'heat' radiation.

Highly radioactive ingot of pure plutonium. Definitely not glowing… so you won't either!

Radium dial painters ca 1920. All died within a few years.

Misconception 1: A person exposed to radiation will become radioactive.

This is **false**. A person becomes 'radioactive' if dust particles containing various radioisotopes or alpha particles land on the persons skin or garments. Once a person has been decontaminated by clothes removal and dermal scrubbing, all of the particulate radioactivity sources are eliminated, and the individual is no longer contaminated.

Misconception 2: People will 'glow in the dark' when contaminated.

This is **false**. There is no physical mechanism involving the emission of visible light that could ever cause a contaminated person to shine visibly. There are no radioisotopes likely to be trapped on dust grains and delivered to bodily surfaces that emit visible-light. There are however 'gamma emitters' that emit gamma rays, and 'beta emitters' that emit electrons, but these are invisible to humans. They can, however, be detected by standard dosimetry techniques, and removed through decontamination.

Misconception 3 – Radiation is always harmful.

This is **false**. It depends on how it is used. For diagnostic medicine or treating cancers, it is obviously beneficial compared to not using it at all. At high levels, however, it invariably leads to an increase in cancers in the exposed human population, which is obviously bad. At low levels, the ability of radiation to alter genetic information and cause mutations may actually be one of the 'driving forces' behind the evolution of life on Earth. As with all other natural phenomena, from ultraviolet rays used in sun tanning, to atomic disintegration used in nuclear fission reactors, radiation and radioactivity can be safely used provided that the proper steps are taken. You do not take a sports car out for a drive at 130 mph without knowing how to drive. Similarly, you do not use radioactivity without properly understanding its impacts.

Misconception 4 - A microSeivert is the same as a microSeivert per hour.

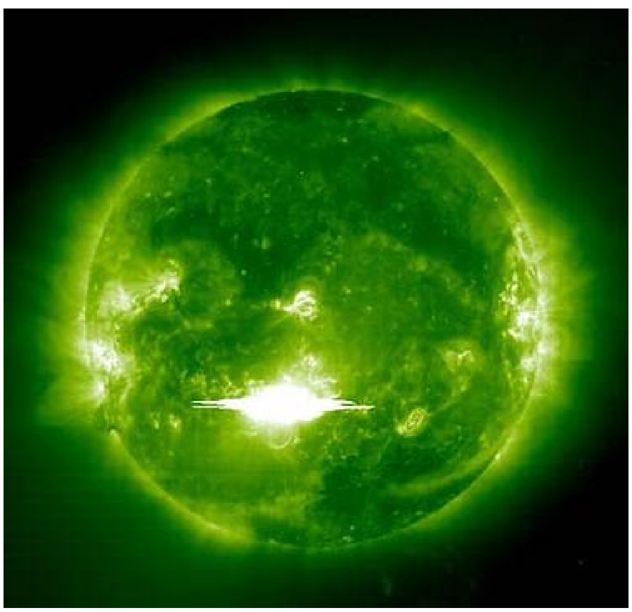
This is **false**. They are as different as 'mile' and 'speed' or 'gallons' and 'mpg'. A microSeivert is the total dose you have accumulated, while a microSeivert per hour is the 'speed' with which you have absorbed the radiation.

Space Weather: The Major Elements

Solar Flares

A solar flare on the sun may last only an hour but is capable of emitting huge amounts of high-energy particles as well as electromagnetic radiation such as ultraviolet and x-rays. The total energy release can be measured in thousands or millions of equivalent hydrogen bombs going off all at once.

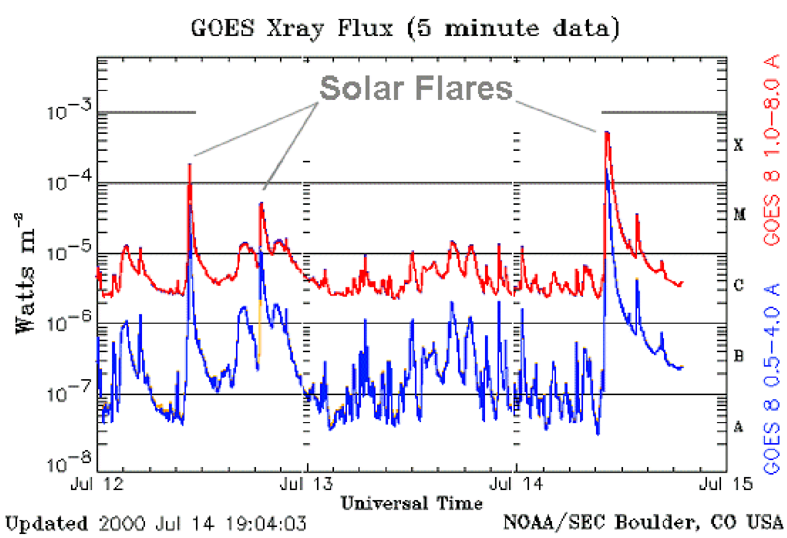
Flares are caused by magnetic fields near sunspots that have become tangled, and over the course of a few hours, release the stored magnetic energy.



Most of this energy causes local heating of the plasma to temperatures as high as 50 million degrees C. This release of energy produces an intense burst of electromagnetic radiation, especially at x-ray energies, but also spanning much of the electromagnetic spectrum from radio to gamma rays as well. Traveling at the speed of light, X-rays can make the journey from the sun to Earth in just under 9 minutes. Accompanying the flare event, particles such as electrons, protons or low-mass atomic nuclei can be accelerated to very high energies, with speeds approaching that of light. If directed towards Earth, these solar energetic particles (SEPs) can make the trip in under an hour. It is usually possible to anticipate what sunspot regions on the sun can produce these flares, but the exact time is not predictable to within a day of the event itself.

Under favorable conditions of Earth-sun geometry, the x-rays can reach Earth and cause heating of the upper atmosphere. As the upper atmosphere expands, satellites in low Earth orbit below 500 km will experience increased drag, causing premature reentry if not corrected. This is generally not a problem for manned flight with destinations beyond Earth, but is a continuing problem for NASA assets such as the International Space Station (ISS). The human consequences of these x-rays are generally modest. Spacesuits and the bulkheads and walls of spacecraft provide excellent shielding so that little excess radiation is biologically absorbed by the x-rays and other electromagnetic components to solar flares.

Solar flares are commonly classified by their X-ray brightness. The graph below shows the x-ray emission from the sun recorded by the GOES satellite, with the solar flares indicated. The 'class' of the flare is noted on the right-hand edge of the graph and is demarcated by a 10x increase in x-ray intensity with each class change upwards. B-class flares are about 10x as intense as A-class flares, while a C-class flare is 10x as intense as a B-class flare and so on.

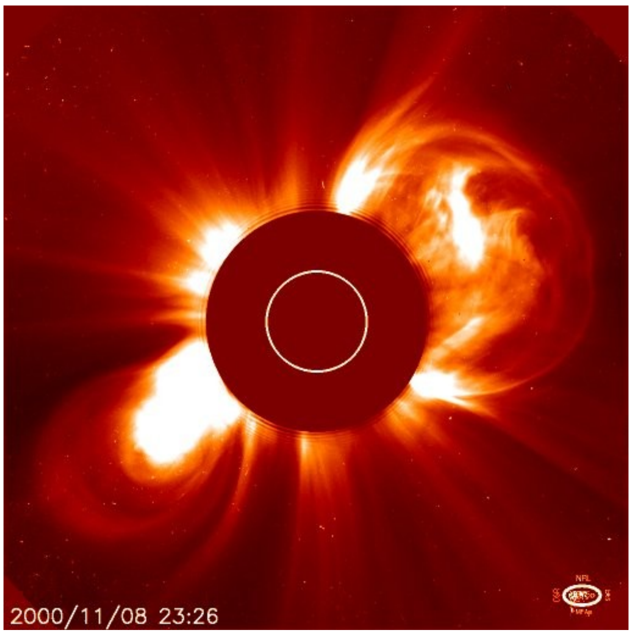


Because of their number, M-class flares can be more of a problem than the X-class flares. Over 16,000 flares were produced on the sun during the last sunspot cycle; Only about 100 of these were X-class flares.

Note how quickly the x-ray intensity increases as the flare reaches its peak. It is not possible to predict in real-time whether a given increase will lead to an X-class event or a less risky C or M-class flare. Accurate classification can only be done after the entire event has completed, which usually takes a few hours after the peak is detected.

Coronal Mass Ejections

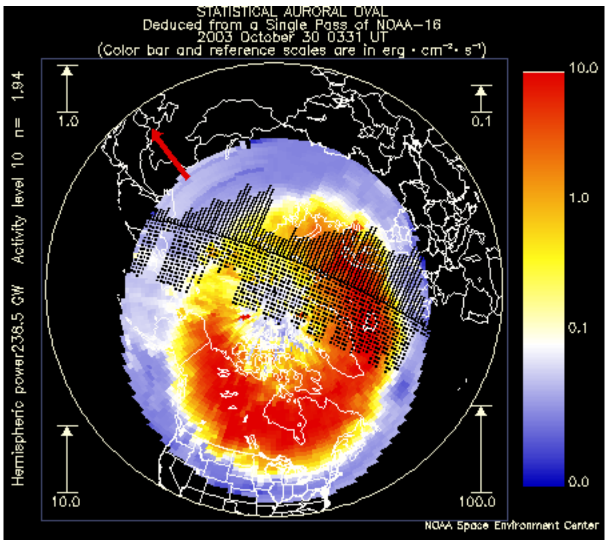
Coronal Mass Ejections (CME) are clouds of plasma and magnetic fields launched from the sun. Most are not directed towards Earth but can nevertheless be viewed leaving the solar vicinity by instruments on the SOHO satellite. They may be caused by magnetic fields in the upper atmosphere of the sun that have become unstable, perhaps because of some powerful disturbance in the solar photosphere or chromosphere such as a large solar flare eruption, or a shockwave from a distant explosion that happens to pass by.



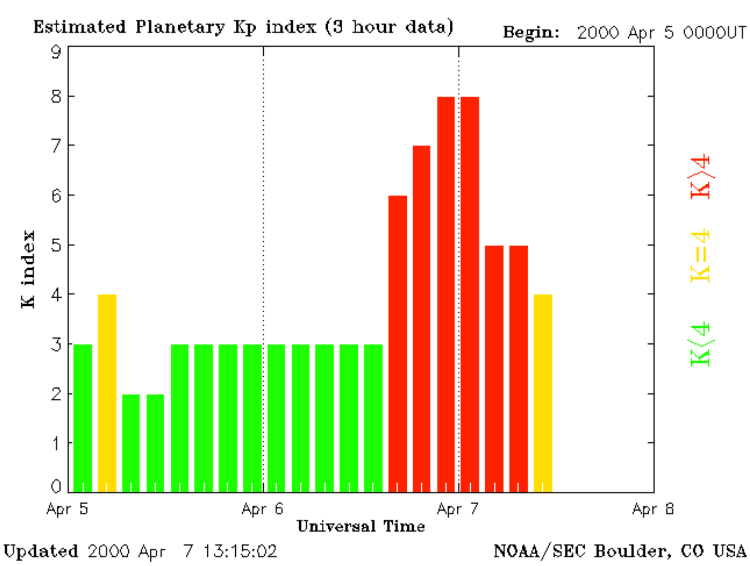
The SOHO satellite detected 1,600 CMEs during the last sunspot cycle between 1996-2008. Many of these were expanding away from Earth because they were produced on the far-side of the sun. About 500 were ejected towards Earth during this 11-year period, mostly during the sunspot maximum years. Most of these Earth-directed CMEs led to minor geomagnetic disturbances because their magnetic fields were oriented in the same direction as Earth's field in the northern hemisphere. 50% of these 'halo' CMEs had favorable 'southward-directed' fields and produced many spectacular aurora and geomagnetic storms. CMEs take up to 4 days to arrive at Earth from the time they are spotted in images such as the one above. The fastest CMEs can make the journey in as little as 15 hours!

Geomagnetic Storms

Arriving at Earth, CMEs compress Earth's magnetic field on the sun-side, and trigger the Northern Lights. They also cause 'geomagnetic storms' which are disturbances in the direction and strength of Earth's magnetic field. Depending on the scale of the CME and its speed, geomagnetic storms can last for hours or entire days at a time. The severity of the event is usually measured by several geophysical indices, Kp and AA, which directly measure the magnitude of the magnetic changes. The Kp index can vary from 1-2 during mild 'stormy' days, to 8-9 for the most intense magnetic storms. The image shows a geomagnetic storm causing an auroral 'oval' over the North Pole. The NPOESS satellite that created this image can measure how active the auroras are at the present time, but cannot be used to predict conditions days or weeks in the future.



This bar graph of Kp index shows a magnetic storm (red) that occurred on April 7, 2000. The index indicated how much change has occurred in the Earth's magnetic field

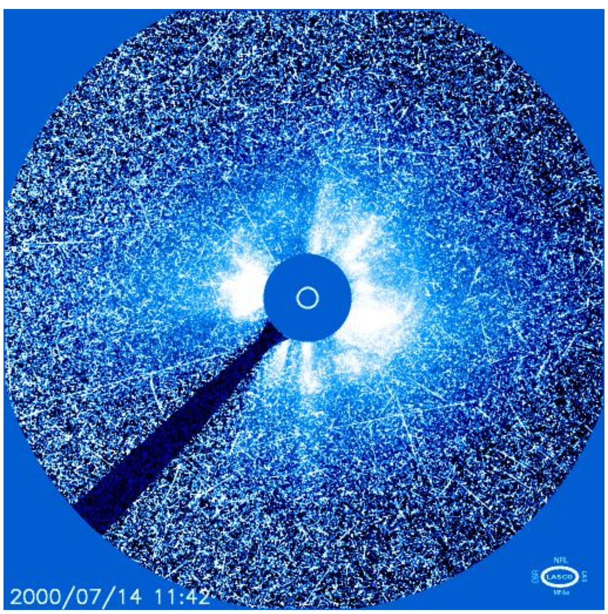


during the previous 3-hours based on 20 observatory measurements on the ground across the globe. Note how quickly conditions changed from a minor Kp=3 condition to a major storm state with Kp=6-8.

Intense geomagnetic and solar storms are rare during times of sunspot minimum, but become more common around sunspot maximum and the years immediately following sunspot maximum. They are also more common during the equinox months of March and September. Although not all solar flares lead to the ejection of CMEs, the most powerful 'X-class' flares often correlate with large CME events. Consequently, the detection of a strong X-flare may be followed within hours of the ejection of a CME. Moreover, some CMEs produce intense bursts of high-energy protons that are accelerated by the compression of the CME magnetic fields. These 'solar proton events' or SPEs are similar to the Solar Energetic Particle (SEP) events produced by solar flares, but can achieve higher particle energies, leading to enhanced electronic anomalies in computers, and harm to astronauts.

The CME compression of Earth's magnetic field can cause currents to flow in the ionosphere that also induce currents in the ground, affecting telegraph systems and electrical power grids worldwide. In space, geomagnetic storms create the conditions that lead to enhanced charging of satellite and spacecraft surfaces. This can led to degradation of solar panels and discharges that lead to false-commands, data corruption and other electronic anomalies. The SPEs that sometimes occur during the initial phases of CMEs can cause satellite anomalies, electronic ‘false commands’ and data corruption. There are no direct human health effects from CMEs, however the SPEs generated by some CMEs each Earth within an hour and cause increased radiation exposure to astronauts, even when shielded inside spacecraft.

CMEs and their associated phenomena can affect electrical systems and cause false-commands and data corruption. Electrical problems from the induced currents only occur after the CME has arrived at Earth. False-commands and other electrical anomalies in satellite electronics can occur soon after the CME is launched from the sun as the SPEs reach Earth. SPEs are hazardous to astronauts, even when they are operating within Earth's magnetic field. Some CMEs may even be lethal if an astronaut is on EVA. Under normal spacecraft shielding conditions, SPEs slightly elevate the accumulated radiation dosages of astronauts. Since exposure and long-term medical conditions are proportional to accumulated dose over a lifetime, astronauts should always seek out additional shielding when a SPE is in progress.



Solar Proton Events

Solar Proton Events (SPEs), and other energetic particle showers are high energy particles that can penetrate spacesuits and spacecraft and lead to excessive radiation dosages that, over the long term, can accumulate to become a significant hazard. Generally, if a solar active region (e.g. sunspot region) is displaying conditions that may lead to a solar flare, a hightened state of alert for potentially ensuing SEPs is warranted. They can be caused by intense solar flares, but are more commonly related to CMEs withing which intense shock waves can accelerate particles to high energy soon after ejection by the sun.

The image from the SOHO satellite shows a Solar Proton Event causing ‘snow’ on an imaging sensor. The SEP particles entered the sensor and corrupted the data in thousands of pixels of the image causing the streaks and white points. This condition faded after a few minutes once the CME ejection near the sun began to abate.

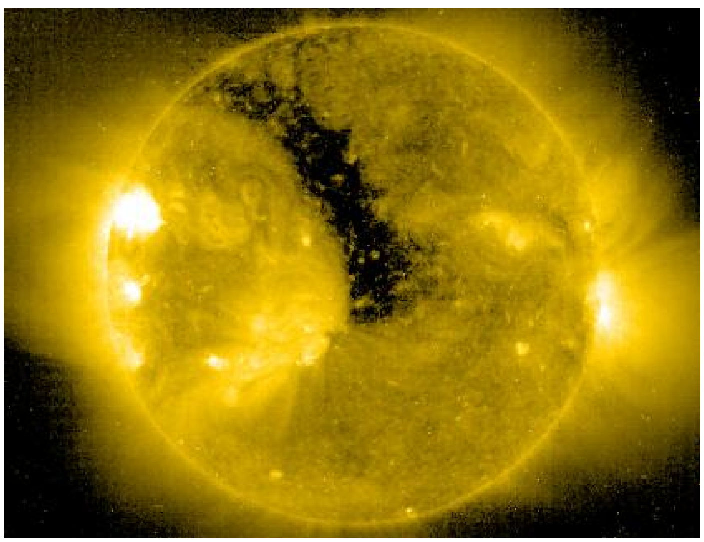
Space walks or other EVAs should probably not be conducted during these states. It is common for ISS astronauts to move operations into more heavily shielded areas of the station for the few hours that an actual flare is in progress, and when SEP particles may be expected to arrive. The arrival of the x-rays is a good harbinger for the SEPs.

Depending on the energy spectrum of the SEPs, they can penetrate many kinds of shielding, and even at low levels, cause computer operations ‘anomalies’. These can include data corruption, or ‘false commands’ which have to be caught and countermanded by satellite or mission operators. At times, computers have to be ‘rebooted’ or suffer operating system anomalies that can lead to lockups. Generally, low-energy SEPs can be shielded and reduced to low levels, but high-energy SEPs generate secondary particles within the shielding itself leading to additional problems.

Solar flare forecasts (e.g. NOAA) usually state conditions as '80% probability of a flare within the next 24-hours'. When solar flare conditions are forecast, Missions can proceed normally, but astronauts should seek additional shielding opportunities if available, and be alert for any false-commands or data irregularities caused by SEP events during the 1-5 hour period following the actual x-ray flare event.

Coronal Holes

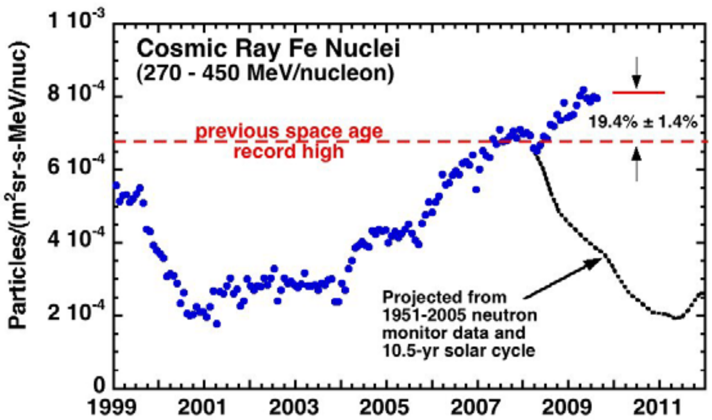
Magnetic fields near the sun sometimes open up into interplanetary space so that charged particles can travel from the sun and deep into interplanetary space. These regions are called coronal holes and are the source of high-speed solar wind streams (HSWS). The pressure of the plasma flowing out of a coronal hole can trigger geomagnetic storms.



As for CME-triggered geomagnetic storms, HSWSs can also produce the Northern Lights, but are not as effective in causing significant electrical disruptions.

Cosmic Rays

These high-energy particles, mostly electrons, protons and low-mass nuclei come from several sources, distant interstellar space beyond our solar system, the heliopause beyond the orbit of Pluto, and the sun itself. Although Earth's magnetic field shields the terrestrial space environment from most of these particles, they are especially common in interplanetary space. During sunspot maximum, the magnetic field of the sun and the solar wind are relatively extended through out the inner solar system, so cosmic ray flows are reduced out to the orbit of mars. During sunspot minimum, the solar field is less extended and so the intensity of cosmic rays in the Earth-mars region is enhanced. Cosmic rays penetrate most forms of shielding, and so remain a hazard to technology and human health.

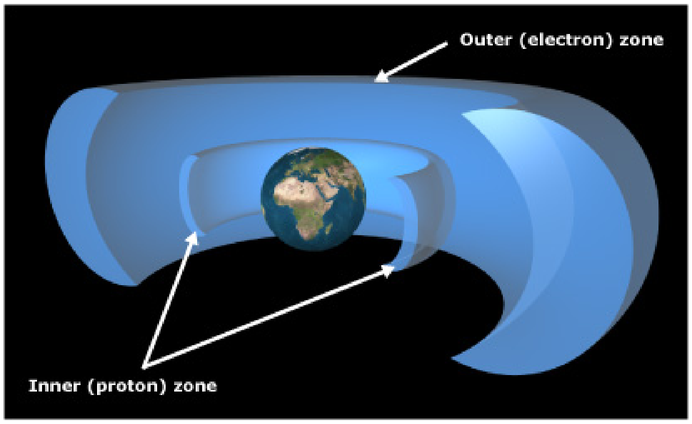


Like SEPs and SPEs associated with solar flares and CMEs, cosmic rays penetrate satellite and spacecraft walls and can cause electrical upsets and 'glitches' in computer systems. These events can cause false-commands and corrupt stored data. Unlike the short-term effects of SEPs and SPEs, cosmic rays are a nearly constant source of background radiation that leads to large accumulated lifetime radiation dosages proportional to the number of days that astronauts are away from Earth and its protecting magnetic field environment.

Cosmic rays contribute to a steady,, daily dose of environmental radiation that is nearly independent of shielding. There is a slight reduction in exposure during times of sunspot maximum conditions provided that astronauts do not leave the inner solar system inside the asteroid belt. The anti-correlation of intensity with solar cycle is the only means of predicting the intensity variation over time. No 'storm' events correlated with cosmic rays are known to exist.

Radiation Belts and Trapped Particles

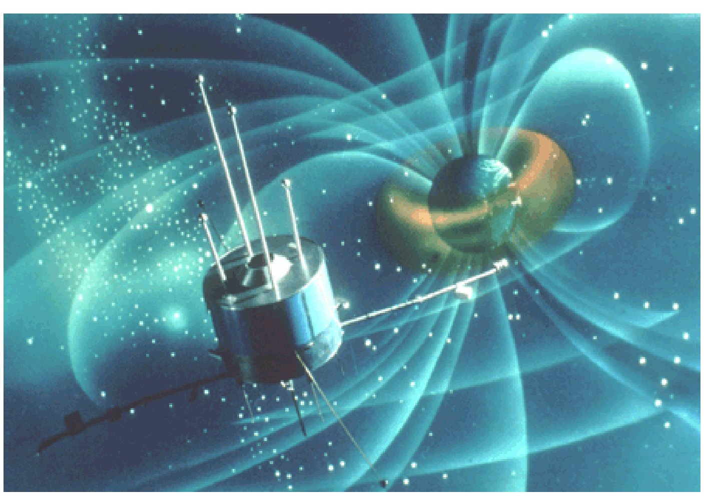
These are found only in the Earth's environment inside its magnetic field in space. They are not an issue for interplanetary or lunar travel. Although prolonged, unshielded exposure to these high-energy particle belts can be lethal, generally, manned spacecraft only take a small part of an hour to traverse these belts, and in most cases, trajectories avoid the belts entirely.



Satellites that orbit in the belts (GPS) experience frequent glitches in operation, and accumulated radiation aging of satellite systems and electronics. Manned space craft spend so little time traversing the Belts that there is no radiation impact to astronauts unless they are conducting EVAs, which is a very unlikely scenario.

Space Weather and Human Impacts

Human life is linked to the behavior of the Sun. Changes in the Sun's long-term brightness cause ice ages, and the 11-year solar cycle of activity causes powerful flares and coronal mass ejections that impact Earth, disrupt telecommunications and navigation, threaten astronauts, damage satellites,



and disable electric power grids. As society becomes increasingly dependent on space-based technologies, humankind's vulnerability to space weather becomes more apparent, and the need to understand and mitigate these effects becomes more urgent.

NASA's objective is to understand and predict the causes of space weather by studying the Sun, the heliosphere, and planetary environments as a single connected system. Research into the nature of solar activity and its effects on the solar system will help safeguard the journeys of robotic and human explorers. (NASA Strategic Plan 2006, sub-goal 3B)

The earliest investigations of how solar storms affect our technology began in the mid-1800's. The appearance of large sunspots was found to be correlated with intense aurora, and with telegraph outages. Since then, scientists have explored and theorized about the many ways in which solar activity can cause communications outages, electrical power blackouts and excess radiation exposure to astronauts and even commercial airline passengers and flight crews.

Space weather research spans both the scientific research community, who are trying to understand the Sun-Earth system, and engineering community who are trying to understand how specific technological systems are affected. Because solar flares can increase radiation exposure to astronauts, NASA has been investigating space weather and its mitigation since the beginning of the Space Age.

Most scientists working in this complex area are supported by a variety of research grants from NASA and from the National Science Foundation. The research is routinely published in the open literature. The Department of Defense and many commercial industries (e.g. satellite and electric power) also have research programs to forecast space weather and its impacts, however, this research is generally classified and not openly published.

Since the first astronaut entered space, NASA has paid close attention to the problem of radiation exposure. Since 1960, over 400 astronauts and cosmonauts have been exposed to the space environment from as little as 90 minutes to over 200 days.

The NASA 'Longitudinal Study' has followed the medical histories of each astronaut in minute detail to uncover any signs that their brief exposures have led to increased risks for a variety of known radiation-related, medical conditions.

Looking farther ahead to years-long expeditions to Mars, NASA scientists and engineers are working to overcome the daunting challenges of minimizing astronaut radiation dosages, and returning the explorers safely to Earth, with no long-term medical problems.

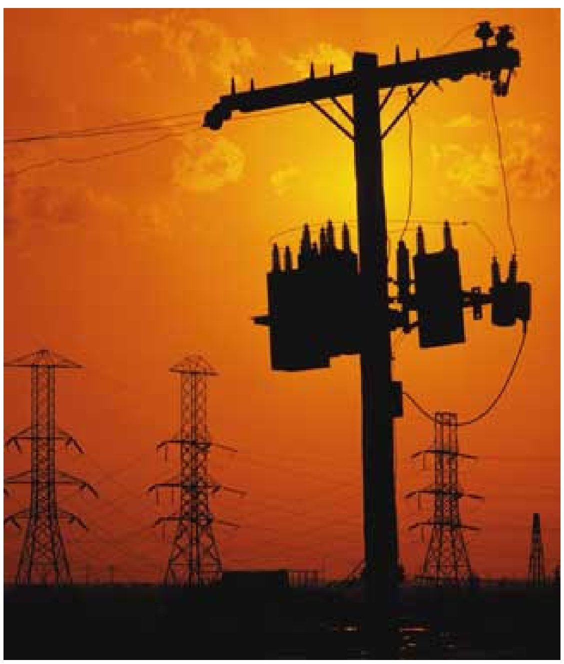
Since scientists first experimented with radioactive elements and explored the mysteries of cosmic rays, the topic of 'radiation' has been a popular science fiction tool to create monsters. In reality, humans live and work in an environment awash in many forms of natural radiation, and have done so for millions of years.

Were it not for this 'background radiation', it is likely that evolution itself would grind to a stop without this relentless mechanism for mutating genes.

Radiation comes in two basic forms: Electromagnetic, and particulate. Each of these forms can be further classified as 'ionizing' or 'non-ionizing' depending on whether the radiation carries enough energy to strip electrons from their atomic imprisonment. Each of these forms has its own complex behavior as it penetrates or is absorbed by matter, whether that matter is in the form of organic material or inert electronic circuitry.

NASA is interested in all forms of radiation that are capable of affecting astronauts and the organic systems they depend on. NASA is also interested in radiation which can alter the operations of electronic circuits which control spacecraft and spacecraft systems.

Solar storms have affected ground-based communications and electrical systems



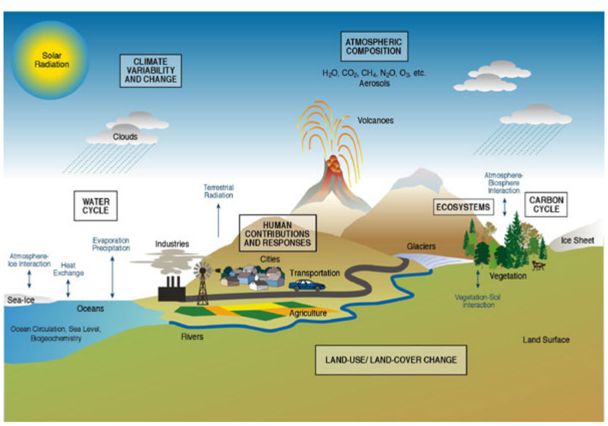
since the time that these systems became commonplace. During the 1800's, telegraph systems were frequently disrupted by severe magnetic storms, such as the spectacular events of August 28 and September 2, 1859.

During the 20th Century, solar flares regularly caused so much interference that global shortwave communications outages were a commonplace nuisance during the 1930's - 1950's.

Once elaborate electrical power grids were installed spanning entire continents, they too fell victim to solar storms, such as the major electrical blackouts in Quebec during March, 13, 1989 and southern Sweden on October 29, 2003.

In order to operate economically, modern passenger jets fly at altitudes above 30,000 feet where the atmosphere is less dense providing less friction and greater fuel economy. With little atmosphere to shield them, passenger jets receive substantially higher dosages of cosmic rays and other forms of natural background radiation. This is especially true along the increasingly popular polar routes from New York to destinations in Eastern Asia such as Tokyo and Beijing. Although ordinary passengers need not worry about the slight increases from occasional solar flares, airline crews are coming under increasing scrutiny because of their constant exposure. Some airline companies such as United and American Airlines now take expensive precautionary steps to move flight paths to lower altitudes during solar flares.

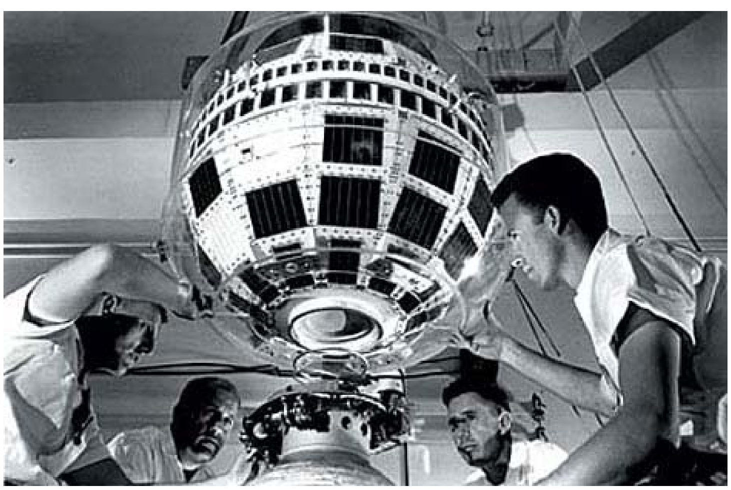
The Maunder Minimum (1645-1715) was a period of time when few sunspots were observed for nearly 70 years, despite careful telescopic studies by multiple observers. This time also corresponded to the European 'Little Ice Age' which brought severe, cold winters to otherwise moderate climates. Scientists now believe that there is a direct connection between sunspot activity and the heating of the atmosphere, which can cause long-term climate changes.



The output of the Sun can vary by up to two tenths of a percent over the 11-year solar cycle. Temporary decreases of up to one-half percent have been observed. Atmospheric scientists say that this variation is significant and that it can modify climate over time. Plant growth has been shown to vary over the 11-year sunspot and 22-year magnetic cycles of the Sun, as evidenced in tree-ring records.

During solar proton events, many more energetic particles reach Earth's middle atmosphere. There they cause molecular ionization, creating chemicals that destroy atmospheric ozone and allow increased amounts of harmful solar ultraviolet radiation to reach Earth's surface. A solar proton event in 1982 resulted in a temporary 70% decrease in ozone densities. During a large solar storm, a portion of the upper stratosphere in the Polar Regions can lose up to 20 percent of its ozone and cool as much as 3°C, an effect that can last for several weeks.

Solar flares and other forms of solar activity have been known to cause problems for satellites and space technology since the dawn of the Space Age.



The first satellite to fail from a space weather event was the Telstar communications satellite launched in July, 1962. A few months later it suffered a malfunction when an electrical component built up a large charge due to constant exposure to the space environment. Technicians powered-down the satellite and then re-started it, which dissipated the extra charge, and the satellite was returned to service. Since then, our current network of over 950 satellites have been affected by solar storms on a regular basis. Most of these effects are brief and barely noticed by ground-based satellite operators. Others have caused complete satellite failure.

Engineers are constantly testing prospective satellite components to make certain that they can withstand the most severe solar storms. The result of this effort has been new generations of satellites that operate for 10 to 15 years or longer, with only occasional episodes of anomalous behavior.

Human Impacts to Astronauts

Lunar Missions: The transit phase is short enough that cosmic rays are not a significant risk factor. It is expected that the 2-3 day journey will not be scheduled during a period when a known solar active region is producing flares or CMEs. If scheduling does not permit launching during a quiet period, magnetically complex regions on the sun will need to be monitored and the NOAA/SEC space weather indices monitored for indications that a solar flare event has a heightened probability. If a halo CME has been launched, and/or an x-ray flare of class M or X detected, astronauts must prepare for the arrival of high-energy particles within the hour. They must return from EVAs and seek out shielded regions in the spacecraft for a duration that could last several hours. Radiation monitors will indicate when the storm event has passed. During the event, computers and other critical digital electronics must also be monitored for signs of data corruption and false-commands. For long-duration stays on the moon, shielding must be available for astronauts either in a landed spacecraft, or beneath lunar regolith in a habitation module.

Mars and Comet Missions: These are long-duration journeys outside Earth's magnetic field. Cosmic rays are a constant background contributing to a steady increase in human dosages. More access to CME plasma will occur as the orbits traverse a lager volume of space through which CMEs are known to travel. As the spacecraft distance from the Earth increases, astronauts will be less and less able to rely on the vantage points provided by Earth-based satellite observations of the sun (SOHO etc) to help forecast upcoming events unless they bring similar imaging technology with them. Increasingly, astronauts will not have advanced knowledge of incoming radiation events being imaged and measured by distant Earth satellites.

Working with Fluence

The number of particles that hit, or pass through, a given area is called the particle fluence. It is determined by dividing the number of particles that were counted, by the area of the surface that they penetrated.

For example, the image on the left shows four arrows that struck the yellow 'bullseye' of the target, which had an area of 16 cm^2, so the fluence would be

$$F = 4 \text{ arrows} / 16 \text{ cm}^2$$
$$= 0.25 \text{ arrows/cm}^2$$

In physics, the fluence of particles and radiation can be related to how much energy they are delivering to a body to cause damage, or how many particles are available to cause glitches in sensitive electronics. Fluence can also be beneficial. If an astronomer wants to study a distant object, they will need to use a telescope to increase the fluence of the faint object so that it can be detected. The higher the fluence, the brighter the image, and the easier it will be to study the object.

Problem 1 - A digital camera requires 5 photons to be delivered to a pixel in the CCD in order for the light to be detected. If the pixels measure 1 micron on a side, what is the fluence in photons/cm^2 ?

Problem 2 - On September 1, 1859 a major solar flare produced a fluence of 1.9×10^{10} protons/ cm^2 at the start of the Carrington Superstorm. The area of Earth facing the flare is given by $A = \pi R^2$ where $R = 6.37 \times 10^8$ cm. If one proton has a mass of 1.6×10^{-27} kg, how many kilograms of protons did Earth gain during this event?

Problem 1 - A digital camera requires 5 photons to be delivered to a pixel in the CCD in order for the light to be detected. If the pixels measure 1 micron on a side, what is the fluence in photons/cm^2 ?

Answer; 1 micron = 10^{-4} cm, so the pixel area is 10^{-8} cm^2. The fluence is then F = 5 photons/10^{-8} cm^2 = **5×10^8 photons/cm^2**.

Problem 2 - On September 1, 1859 a major solar flare produced a fluence of 1.9 x 10^{10} protons/ cm^2 at the start of the Carrington Superstorm. The area of Earth facing the flare is given by $A = \pi R^2$ where R = 6.37×10^8 cm. If one proton has a mass of 1.6 x 10^{-27} kg, how many kilograms of protons did Earth gain during this event?

Answer: Area of Earth facing the sun A = 1.3 x 10^{18} cm^2. Total mass = Fluence x Area x mass of proton so M = (1.9 x 10^{10} protons/ cm^2)(1.3 x 10^{18} cm^2) (1.6 x 10^{-27} kg/proton) so **M = 40 kilograms**.

The number of particles that hit, or pass through, a given area in a given amount of time is called the particle flux. It is determined by dividing the number of particles that were counted, by the area of the surface that they penetrated, and dividing by the amount of elapsed time.

For example, the image on the left shows four arrows that struck the yellow 'bullseye' of the target within 1 minute. The target had an area of 16 cm^2, so the flux would be

F = 4 arrows / 1 minute/16 cm^2

= 0.25 arrows/minute/cm^2

In physics, particle or radiation flux can be related to how much power is being delivered to a body to cause damage, or how many particles are available to cause glitches in sensitive electronics in a given amount of time. Flux is related to fluence, which is measured in particles/cm^2, by including information about the amount of time over which the fluence was measured. It represents a rate of arrival of particles passing across a given area of surface.

A large fluence can arise from particles flowing with a low flux, but over a long period of time. A large flux, on the other hand, can occur with a small particle fluence delivered over a very short time. In other words, Flux = Fluence / Time or alternatively, Fluence = Flux x Time.

Problem 1 - A cosmic ray detector has a collecting area of 1500 cm^2. It records 20,000,000 cosmic ray events in 1 hour. What is the flux of the cosmic rays in particleds/cm^2/sec?

Problem 2 - In order to register on an instrument, 100,000 particles have to be collected. If the particle flux is 1,000 particles/cm^2/sec, and the detector has an area of 10 cm^2, how long will it take to accumulate the required number of particles?

Problem 1 - A cosmic ray detector has a collecting area of 1500 cm^2. It records 20,000,000 cosmic ray events in 1 hour. What is the flux of the cosmic rays in particleds/cm^2/sec?

Answer: F = 20,000,000 particles x (1 / 1500 cm^2) x (1/1 hour) x (1 hour/3600 seconds) so **F = 3.7 particles/cm^2/sec**.

Problem 2 - In order to register on an instrument, 100,000 particles have to be collected. If the particle flux is 1,000 particles/cm^2/sec, and the detector has an area of 10 cm^2, how long will it take to accumulate the required number of particles?

Answer: 1000 particles/cm^2/sec x 10 cm^2 = 10^4 particles/sec.

Then

T = 10^5 particles x (1 sec/10^4 particles)

= **10 seconds**.

Radiation Measurement - Grays and Rads

Apart from the many different forms of 'radiation', there are a bewildering number of units for reporting radiation intensity. Chief among these are the units of grays and rads. These are perhaps the simplest units because they are directly related to easily understandable physical properties of matter.

1 gray (1 Gy) is equal to 1 joule of energy delivered to 1 kilogram of matter (1 J/kg). It does not matter what kind of matter is doing the absorbing. It can be biological tissues, solid rock, million-dollar microcircuitry or a tank of pure water. The gray is part of the SI unit convention in which basic physical units are reported in meters, kilograms and joules. This unit was named in honor of the British physicist Louis Harold Gray (1905-1965) who was active in precisely measuring the amount of energy delivered to matter by radiation. Note that when you write-out this unit you do not capitalize it, but only do so when you abbreviate it as a unit (1 Gy).

1 rad (1 Radiation Absorbed Dose) is equal to 100 ergs of energy absorbed by 1 gram of matter. Like the gray, the nature of the matter does not matter. First proposed in 1918, it has fallen out of use in most countries except the United States. The conversion from gray to rad is simple. 100 rads = 1 gray, or 1 centi-gray (1cGy) = 1 rad.

Problem 1 - Convert a dose rate of 1 Gy/day into the following equivalent units:

A) milliGy/hour

B) kiloRads / year

Problem 2 - A solar proton event lasts for 15 minutes and exposes the shielded astronauts to a radiation dose rate of 0.01 rads/minute. A) What is the equivalent dose rate in micrograys/minute? B) Why is it inappropriate to measure the dose rate in units of rads/year?

Problem 1 - Convert a dose rate of 1 Gy/day into the following equivalent units:

A) milliGy/hour

Answer; D = 1 Gy / day x (1 day / 24 hr) x (1000 milli / 1)
= 41.7 milliGy/hr

B) kiloRads / year

Answer: D = 1 Gy/day x (365 d / 1 yr) x (100 rads / 1 Gy) x (0.001 kilo / 1)
= **36.5 kiloRads/yr**.

Problem 2 - A solar proton event lasts for 15 minutes and exposes the shielded astronauts to a radiation dose rate of 0.01 rads/minute. A) What is the equivalent dose rate in micrograys/minute? B) Why is it inappropriate to measure the dose rate in units of rads/year?

Answer: A) D = 0.01 rads/minute x (1 gray / 100 rads) x (1 million micro/ 1)
= 0.0001 x 1 million micro rads/minute
= **100 microRads/minute**.

B) Because the radiation event only lasted 15 minutes and there is no justification for physically referring the intensity to an annual scale. Also, a prompt radiation dose delivered in 15 minutes does not have the same consequences as the same amount of radiation delivered over a year-long baseline.

Apart from the many different forms of 'radiation', there are a bewildering number of units for reporting radiation intensity. Although grays (rads) are used to measure the amount of energy delivered to a specific amount of matter, what we really want to keep track of is how much biological damage this energy does after it is absorbed. (Note: 1 gray = 100 rads)

Because there are many forms of radiation, and each of these has different biological consequences, a new unit called the rem was devised. Rem is short for Roentgen Equivalent Man, and it is related to the absorbed dose measured in rads according to **Rem = Q x Rad**. The variable 'Q' is a quality factor that is different for the various forms of radiation harmful to humans and living organisms. The table below give some popular values:

Radiation	Q
X-rays, gamma-rays or electrons	1
Neutrons (all energies)	10
High-energy protons	10
Alpha-particles and ions	20

A radiation unit related to the rem is the sievert (Sv), which is defined according to sievert = Q x gray. The same quality factor is used in this conversion as for rem = Q x rad. This also means that 1 sievert = 100 rems.

Problem 1 - A radiation source produces 1 rad/day of x-rays, 3 rads/day of gamma-rays and 5 rads/day of high-energy protons. What is the total dose you would expect in rems/day from this source?

Problem 2 - The radiation environment on the International Space Station produces background radiation dose rates for the astronauts of about 1.2 milliSieverts/day. Convert this to the following units:

A) microSieverts/hour

B) milliRem/hour

C) sieverts/year

D) grays/hour of neutron radiation.

E) rads/hour of alpha particles

Problem 1 - A radiation source produces 1 rad/day of x-rays, 3 rads/day of gamma-rays and 5 rads/day of high-energy protons. What is the total dose you would expect in rems/day from this source?

Answer: rems = Q x rads
Dose = (1) x 1 rad/day + (1) x 3 rads/day + (10) x 5 rads/day
= 54 rems/day

Problem 2 - The radiation environment on the International Space Station produces background radiation dose rates for the astronauts of about 1.2 milliSieverts/day. Convert this to the following units:

A) microSieverts/hour

Answer: D = 1.2 milliSv/day x (1000 microSv/1 milliSv) x (1 day / 24 hr)
= **50 microSv/hr**.

B) milliRem/hour

Answer: D = 1.2 milliSv/day x (1 day/24hr) x (100 rem/1 seivert)
D = **5 milliRem/hr**.

C) sieverts/year

Answer: D = 1.2 milliSv/day x (365 day / 1 yr) = 438 milliSv/yr
D = **0.438 Sv/yr**.

D) grays/hour of neutron radiation.

Answer: 1 sievert = Q x 1 gray. For neutrons Q = 10, so 1 Sv = 10 Gy, then

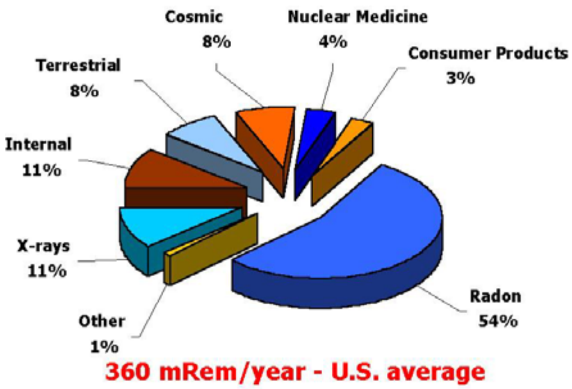
D = 1.2 milliSv/day x (10 Gy / 1 Sv) x (1 day / 24 hr)
D = **0.5 milliGy/hr**.

E) rads/hour of alpha particles

Answer: 1 rad = Q x 1 rem, and for alpha particles, Q = 20, so 1 rad = 20 rems.

D = 1.2 milliSv/day x (100 rems / 1 Sievert) x (1 rads / 20 rem) x (1 day / 24 hr)
= 0.25 millirads/hr
= **0.00025 rads /hr**.

Radiation Unit Conversion Exercises



To understand the effect that radiation has on biological systems, a number of different systems for measurement have arisen over the last 50 years. European scientists prefer to use Grays and Seiverts while American scientists still use Rads and Rems!

The chart to the left shows your typical radiation dosage on the ground and the factors that contribute to it.

1 Gray = 100 Rads		**0.001**	**milli**
1 Rad = 0.01 Joules/kg		**0.000001**	**micro**
1 Seivert = 100 Rems		**1 lifetime**	**= 70 years**
	1 year = 8760 hours		

In the problems below, use the above table to solve for the new units:

1 . 360 milliRem per year to …………………………..microSeiverts per hour

2. 7.8 milliRem per day to …………………………..Rem per year

3. 1 Rad per day to ……………………………………Grays per year

4. 360 milliRem per year to ……………………………Rems per lifetime

5. 5.6 Seiverts per year to ……………………………milliRem per day

6. 537.0 milliGrays per year to ……………….……..milliRads per hour

Unit Conversion Exercises

Answer Key

1 . 360 milliRem per year to ……………………………**0.41 microSeiverts per hour**
360 milliRem/yr x 1Rem/1000 milliRem x 1 year/8760 hours = 0.000041 Rem/hour
0.000041 Rem/hour x 1.0 Seiverts/100 Rem = 0.00000041 Seiverts/hour
0.00000041 Seiverts/hour x 1 microSeivert/0.000001Seivert = 0.41 microSeiverts/hour

2. 7.8 milliRem per day to ……………………….……**2.8 Rem per year**
7.8 milliRem/day x 365 days/year = 2847.0 milliRem/year
2847.0 milliRem/year x 1.0 Rem/1000milliRem = 2.8 Rem/year

3. 1 Rad per day to …………………………………..…**3.65 Grays per year**
1 Rad/day x 365 days/year x 1 Gray/100 Rads = 3.65 Grays/year

4. 360 milliRem per year to ………………………………**25.2 Rems per lifetime**
360 milliRem/year x 70 years/lifetime x 1 Rem/1000 milliRem = 25.2 Rems/lifetime

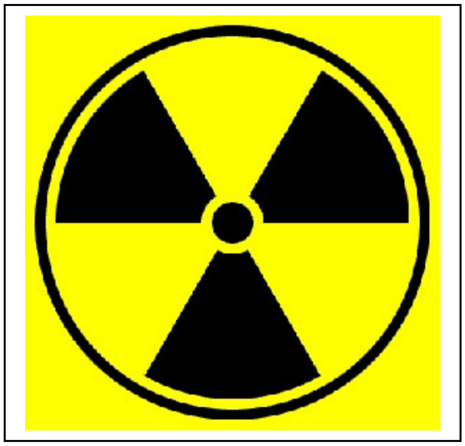
5. 5.6 Seiverts per year to ………………………………**1530 milliRem per day**
5.6 Seiverts/year x 1.0 Year/365 days x 100 Rem/1.0 Seivert = 1.53 Rem/day
1.53 Rem/day x 1000 milliRem/Rem = 1530 milliRem/day

6. 537.0 milliGrays per year to …………………………**6.13 milliRads per hour**
537.0 milliGrays/year x 1.0 years/8760 hours x 100 Rads/1.0 Gray = 6.13 milliRads/hour

Teacher Note: There are many different conversion 'chains' that the students can offer. The challenge is to set up each ratio correctly with the right number in the numerator and denominator! Many errors are made in science and engineering because someone didn't do a conversion chain properly!! All conversion chains are algebraic statements where identical quantities in the numerator and denominator cancel. For example:

$\frac{1\,\mathrm{Re}\,m}{24hr} x \frac{24hr}{1Day} = \frac{1\,\mathrm{Re}\,m}{day}$ is just like the algebraic statement $\frac{AxC}{CxD} = \frac{A}{D}$

Radiation Dose and Dose Rate



Radiation is measured in two units. The first is a measure of the rate at which you are being exposed to a source of radioactivity, while the second is a measure of how much total radiation you have accumulated over time.

Radiation dose rate is measured in terms of dose per unit time such as microSeiverts per hour or milliSeiverts per year.

Radiation dose is measured in units of microSeiverts while

Hasty reports about the devastating Japan 2011 nuclear power plant radiation leakages have occasionally confused these two concepts. When you consider the analogy of filling up a 1-liter kettle of water from the water tap, it is easy to keep the distinction between dose and dose rate clear. The volume of water in the kettle (the dose) depends on the rate of water flow (the dose rate) times the filling time.

Problem 1 - The natural radiation background at sea level is about 0.4 microSeiverts/hour. In terms of milliSeiverts, what is your total radiation dose after A) 1 year? B) a 70-year lifetime?

Problem 2 - At the typical cruising altitude of a passenger jet, about 10,000 meters (33,000 feet), the dose rate is about 5 microSeiverts/hour. During its years of operation, the French Concorde jet traveled at altitudes of 18,000 meters (54,000 feet) where the cosmic radiation dose rate was about 15 microSeiverts/hour. If a flight from Paris to New York takes 8 hours by ordinary jet and 3.5 hours by Concorde, what are the total radiation doses for a passenger in each case?

Problem 3 - The Japan 2011 earthquake damaged several nuclear reactors, causing radiation leakage across northern Japan. On March 22, 2011 typical radiation levels across most of Japan are now below 50 microSeiverts/hour. The typical annual radiation dose from all forms of natural sources, medical tests, and food consumption is about 0.4 milliSeiverts. How many days will it take for a Japanese citizen to reach this annual dose level?

Problem 1 - The natural radiation background at sea level is about 0.4 microSeiverts/hour. In terms of milliSeiverts, what is your total dose after A) 1 year? B) a 70-year lifetime? Answer: A) 0.4 microSeiverts/hour x (24 hours/1 day) x (365 days/1 year) = 3500 microSeiverts. Converting this to milliSierverts: 3500 microSeiverts x (1 milliSeivert/1000 microSeiverts) = **3.5 milliSeiverts**. B) In a 70-year lifetime ,your total dose will be 70 years x 3.5 milliSeiverts/year = **245 milliSeiverts**.

Problem 2 - At the typical cruising altitude of a passenger jet, about 10,000 meters (33,000 feet), the dose rate is about 5 microSeiverts/hour. During its years of operation, the French Concorde jet traveled at altitudes of 18,000 meters (54,000 feet) where the cosmic radiation dose rate was about 15 microSeiverts/hour. If a flight from Paris to New York takes 8 hours by ordinary jet and 3.5 hours by Concorde, what are the total doses for a passenger in each case?

Answer: Ordinary jet: 5 microSeiverts/hour x 8 hours = **40 microSeiverts**.
Concorde: 15 microSeiverts/hour x 3.5 hours = **53 microSeiverts**.

Problem 3 - The Japan 2011 earthquake damaged several nuclear reactors, causing radiation leakage across northern Japan. On March 22, 2011 typical radiation levels across most of Japan are now below 10 microSeiverts/hour. The typical annual radiation dose from all forms of natural sources, medical tests, and food consumption is about 0.4 milliSeiverts. How many days will it take for a Japanese citizen to reach this annual dose level?

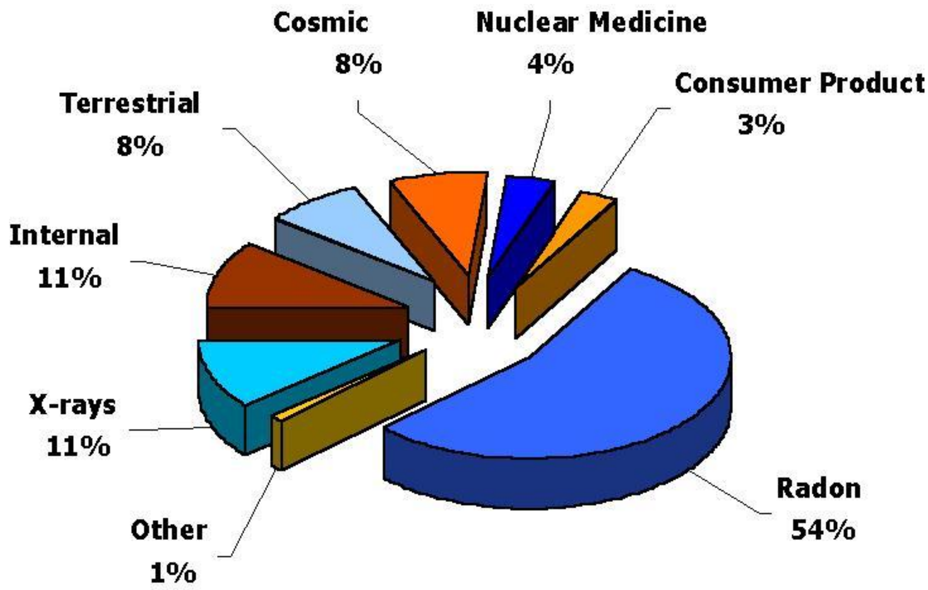
Answer: Time = Amount / Rate

$$Time = \frac{0.4 milliSeiverts}{10 microSeiverts / hr}$$

$$Time = \frac{400 microSeiverts}{10 microSeiverts / hr}$$ so Time = 40 hours.

This means that in one year they will accumulate over 88 milliSeiverts of radiation dose, which is 88/0.4 = 220 times the normal annual dosage.

Fortunately, the dose rates are declining each day as the radioactive isotopes decay, and are also diluted through wind action. The actual accumulated dose may only be 10% of this in most regions of the country. This is still, however, 20 times the natural pre-contamination dose rate. Other communities where the dose rates are higher than 10 microSeiverts/hr will have to be decontaminated by soil removal and other time-consuming and expensive methods.



Our exposure to many unavoidable sources of radiation is a fact of life, and one that can seldom be modified by simple lifestyle changes. Each year, on average, a single human is exposed to sources of radiation from the food supply, cosmic rays, the ground beneath your feet and various medical diagnostic and treatment regimens. Health physicists, professionals who monitor and determine the consequences of human radiation impacts, have estimated that the average human accumulates about 365 millirem/year (3.65 milliSeivert/year) as a typical radiation 'background' exposure. The pie graph above shows the breakdown of this exposure in terms of the known categories of sources.

Problem 1 - A health physicist wants to study the day-to-day exposure changes using a device called a dosimeter. What is the daily radiation exposure rate in A) milliRem? B) microSeiverts?

Problem 2 – On the pie graph above, three categories are natural and unavoidable (terrestrial, internal and cosmic) while four categories can be altered by lifestyle choices (Radon, X-rays, Nuclear medicine and consumer products). What is the total exposure rate from the natural, and the total exposure rate from the lifestyle contributions to your annual background exposure in A) milliRem/year B) microSeiverts/day?

Problem 3 - The Japan 2011 earthquake caused nuclear power plant exposures amounting to an additional 50 microSeiverts/hour for someone living 30 km from the Fukushima Nuclear Plant. A) How many microSeiverts is this per day? B) In terms of the three components 'Lifestyle', 'Natural' and 'Fukushima', how will the percentage contributions to the daily radiation dose change when the Fukushima source is included in terms of microSeiverts/day?

Problem 1 - A health physicist wants to study the day-to-day exposure changes using a device called a dosimeter. What is the daily radiation exposure rate in A) milliRem? B) microSeiverts?

Answer: 365 milliRem/year x (1 year/365 days) = **1 milliRem/day**. B) 3.65 milliSeiverts/year x (1 year/365 days) x (1,000 microSeiverts/1 milliSeivert) = (0.01)x (1000) = **10 microSeiverts/day**.

Problem 2 - On the pie graph, three categories are natural and unavoidable (terrestrial, internal and cosmic) while four categories can be altered by lifestyle choices (Radon, X-rays, Nuclear medicine and consumer products). What is the total exposure rate from the natural, and the total exposure rate from the lifestyle contributions to your annual background exposure in A) milliRem/year B) microSeiverts/day?

Answer:

Unavoidable	**Lifestyle**
Terrestrial = 8%	Radon = 54%
Internal = 11%	X-rays = 11%
Cosmic = 8%	Medicine = 4%
	Consumer = 3%
Total = 27%	**Total = 72%**

A) For 365 milliRem/year:

Unavoidable = 0.27 x 365 milliRem/year = **99 milliRem/year**

Lifestyle = 0.72 x 365 milliRem/year = **263 milliRem/year**

B) For 10 microSeiverts/day:

Unavoidable = 0.27 x 10 = **2.7 microSeiverts/day**

Lifestyle = 0.72 x 10 = **7.2 microSeiverts/day**.

Problem 3 - The Japan 2011 earthquake caused nuclear power plant exposures amounting to an additional 50 microSeiverts/hour for someone living 30 km from the Fukushima Nuclear Plant. A) How many microSeiverts is this per day? B) In terms of the three components 'Lifestyle', 'Unavoidable' and 'Fukushima', how will the percentage contributions to daily dosage change when the Fukushima source is included in terms of microSeiverts/day? Answer: If the pie graph is based upon 10 microSeiverts/day total, of which 2.7 microSeiverts/day are unavoidable background radiation, and 7.2 microSeiverts/day are from various Lifestyle choices. Then:

A) The Fukushima radiation at 30 kilometers is 50 microSeiverts/hour or in terms of a daily dosage, 24 hours x 50 microSeiverts/hour = **1200 microSeiverts/day.**

B) The total dose would be 2.7 + 7.2 + 1200 = 1210 microSeiverts/day. The contributions would then be

Unavoidable = 100% x (2.7/1210) so **Unavoidable = 0.2 %**

Lifestyle = 100% x (7.4/ 1210) so **Lifestyle = 0.6 %**

Fukushima = 100% (1200/1210 so **Fukushima = 99%**

Lifestyles and Radiation Dose

The amount of radiation you receive each year depends on where you live and your lifestyle. Do you live near the coast or in the mountains? Do you travel by jet a lot? Do you have frequent medical diagnostic tests? All of these factors will add together to change your annual radiation dose.

The chart below gives a few common contributors to your dose. These include both geographic and lifestyle factors. The units include both dose and dose rates as appropriate to the factor.

Factor	Dose Rate
Lives in Denver, Colorado	0.90 milliSv/yr
Air travel	5 microSv/hr
Live in a brick/stone house	0.70 milliSv/yr
Watch TV	10 microSv/yr
One CT scan	7 milliSv/scan
Radon gas in basement	1.50 milliSv/yr
Eating one banana	0.1 microSv
Your body	1.5 microSv/day
Smoke 1 pack a day	10 milliSv/day
Lives in Boston, Mass.	0.20 milliSv/yr
Astronaut on Space Station	1.2 milliSv/day

Problem 1 - In 2011, Anders Olssen lived in Denver, Colorado for 6 months then moved to Boston, Massachusetts for the remainder of the year. He was a non-smoker, who lived in a quaint stone house on Beacon Hill. He telecommuted 8 hours a day from his basement office, and enjoyed a banana for lunch every day. What is the total radiation dose for this individual in an average year, in units of milliSeiverts?

Problem 2 - Create a more complicated history for Anders by including a stint on the International Space Station, or including possible medical diagnostic procedures!

Factor	Dosage
Lives in Denver, Colorado	0.90 milliSv/yr
Air travel	5 microSv/hr
Live in a brick/stone house	0.70 milliSv/yr
Watch TV	10 microSv/yr
One CT scan	7 milliSv/scan
Radon gas in basement	1.50 milliSv/yr
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Your body	1.5 microSv/day
Smoke 1 pack a day	10 milliSv/day
Lives in Boston, Mass.	0.20 milliSv/yr
Astronaut on Space Station	1.2 milliSv/day

Problem 1 - In 2011, Anders Olssen lived in Denver, Colorado for 6 months then moved to Boston, Massachusetts for the remainder of the year. He was a non-smoker, who lived in a quaint stone house on Beacon Hill for 6 months. He telecommuted 8 hours a day from is basement office, and enjoyed a banana for lunch every day. What is the total radiation dose for this individual in an average year, in units of Seiverts?

Answer: Denver for 6 months = 0.90 milliSv/yr x 0.5 yr = 0.45 milliSeiverts.
Boston for 6 months = 0.20 milliSV/yr x 0.5 years = 0.1 milliSeiverts
Stone house living = 0.70 milliSv/yr x 0.5 year = 0.35 milliSeiverts
8 hr/day exposure to Radon gas: 1.50 milliSV/yr x 1/3 = 0.50 milliSeiverts
1 banana a day = 0.1 microSv/banana x 365 banana = 36.5 microSeiverts

We also have to add the radiation from his own body!
= 1.5 microSV/day x 365 days = 0.55 milliSeiverts

The total is 0.45 + 0.1 + 0.35 + 0.5 + 0.036 + 0.55 = **2.0 milliSeiverts for a full year**.

Note: typical values on the surface of Earth are between 2.0 and 4.0 milliSeiverts/year, however some inhabited locations on Earth have total rates as high as 7.0 milliSeiverts/year because communities are built on uranium-rich sands, soils and granite deposits.

Problem 2 - Remember that when the astronaut is on the space station, you do not include his exposure to ground-level sources such as radon gas, or living in a different geographic location, during the in-space portion of his life!

A Perspective on Radiation Doses

Space travel is a risky business. One of the most well-studied, and worrisome, hazards is the radiation environment.

But how bad is space travel compared to just staying on Earth? We can answer this question by determining the average dose rates that a person is exposed to each year as they move from place to place, change their elevation, and alter their lifestyles. Each of these causes a change to the 'normal' background dose you will accumulate over your lifetime.

Problem 1 - Nancy was born and raised in Denver where her radiation dose rate was 350 milliRems/year. At age 25, she moved to Houston where her dose rate was 225 milliRems/year, then moved to South Dakota 10 years later where her dose rate was 450 milliRems/year until she retired at age 65.

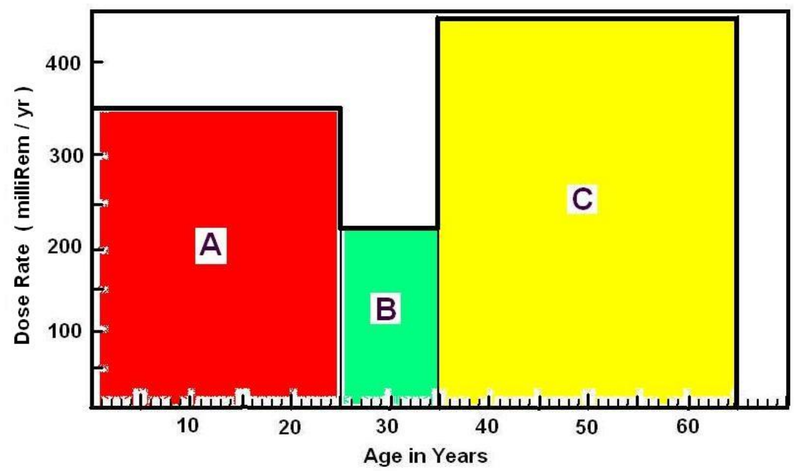
A) Create a plot showing 'Year' on the horizontal axis and 'Dose' on the vertical axis. Plot Nancy's annual doses.

B) Calculate her total exposure by age 65 by adding up the rectangular areas under the dose rate curve. (Note that the product of the vertical axis units times the horizontal axis units is the total dose in milliRems)

Problem 2 - What was her average dose rate in microSieverts/day during the 65-year period staying on the ground? (1 Sievert = 100 Rems)

Problem 3 - Suppose she spent 90 days on the International Space Station where the dose rates are about 1.2 milliSieverts/day. How much additional lifetime dose will she absorb?

Answer Key



Problem 1 : **Answer:** A) See above graph.

B) Add up the areas of the rectangles in the plot above
(Note: dose rate x time interval = dose):

A = (350 mRem/yr x 25 yrs)
= 8,750 mRem;
B= (225 mRem/yr x 10 yrs)
= 2,250 mRem
C = (450 mRem/yr x 30 yrs)
= 13,500 mRem.

Total A+B+C = 24,500 mRem.

Since 1,000 milliRem = 1 Rem, the total exposure **24.5 Rem**.

Problem 2 - What was her average dose rate in microSieverts/day during the 65-year period?

Answer: 1 Sievert = 100 Rem, so in 65 years she received 0.25 Sieverts. Since T = 65 yrs x 365 days/yr = 23725 days, the average dose rate was 0.25 Sieverts/23725 days = **10 microSieverts/day**.

Problem 3 - Suppose she spent 90 days on the International Space Station where the dose rates are about 1.2 milliSieverts/day. How much additional lifetime dose will she absorb?

Answer: 90 days x 0.0012 Sieverts/day = **0.11 Sieverts**. Compare this to the 0.25 Sieverts she receives living on Earth, for a total lifetime dose of 0.36 Sieverts. Her stint on the ISS increased her lifetime dose by nearly 50%!

Radiation Dose and Cancer Risks

It is well known from studies conducted over the last 70 years that, when cells are exposed to radiation, damage can occur that is either repaired if the doses are low, or improperly repaired or fatally damaged if the doses are too high. The specific damage depends on the type of cell tissue (organ) involved, its stage of reproduction, and other factors.

The National Council on Radiation Protection and Measurement estimates the increased cancer risk probability for a population of all ages at 0.05 per Sievert. For example, the estimated number of additional cancer deaths for the population to a dose of 200 microSieverts is equal to: 0.05 x 0.000200 = 1 additional cancer in a population of 100,000.

Because the impacts for most kinds of radiation doses are so small, another way to look at the health risk of radiation is the number of days lost by an individual due to early death. For example, an occupational dose of 0.01 Sievert/year would produce a 51-day 'premature' loss of life expectancy. By comparison, being 15% overweight results in a 2-year loss of life expectancy.

Problem 1 - Airline flight crews travel about 900 hours each year, and are exposed to background rates of about 7 microSieverts/hr.

A) What is the cumulative dose for a 20-year flight career?

B) If the cancer rate and days-lost vary linearly with the dose, what would you estimate as the impact to an individual crew member, and a population of 100,000 flight crew members?

In addition to an increased cancer risk due to their travels in space, astronauts also suffer from a marked increase in cataracts compared to the 'stay-at-home' population. Astronauts have reported for decades that they can often see 'shooting stars' which turned out to be high-energy particles penetrating their eyes, especially during intense solar storms. These particles, over time, lead to damage in the cornea and cause the cornea to become cloudy; a condition called a cataract. Although the cataracts do not actually form immediately, astronauts have a significant risk for cataract formation long after they return to Earth. For astronauts that receive a total of 45 milliSieverts of additional radiation exposure in space, only 60% survive to age 65 without having cataracts compared to 90% of the 'low-risk' astronauts receiving less than 4 milliSieverts.

Problem 2 - Apollo-17 astronauts spent 22-hours in spacesuits on the lunar surface out of a 75-hour stay on the lunar surface, and a mission duration of 12 days. The total dose per astronaut was 5.5 milliSieverts. Assuming that most of the exposure came from spacesuit activity, what might be the cataract risk for future lunar explorers who may spend 3 months on the lunar surface and perhaps 3-hrs/day in spacesuits?

Life expectancy estimates are taken from the NRC Draft guide DG-8012 and were adapted from B.L Cohen and I.S. Lee, "Catalogue of Risks Extended and Updates", *Health Physics*, Vol. 61, September 1991.

See also, 'Space Radiation and Cataracts in Astronauts' , F. A. Cucinotta et al., Radiation Research, v. 156 pp. 460-466., 2001.

Problem 1 - Airline flight crews travel about 900 hours each year, and are exposed to background rates of about 7 microSieverts/hr. A) What is the cumulative dose for a 20-year flight career? B) If the cancer rate and days-lost scale linearly with the dose, what would you estimate as the impact to an individual crew member, and a population of 100,000 flight crew members?

Answer:
A) Cumulative dose = 7 microSieverts/hr x 900 hrs/yr = 0.0063 Sv/year
Then 0.0063 Sv/yr x 20 years = 0.13 Sieverts.

B) From 0.05 deaths/Sievert we have 0.05 x 0.13 = 0.0065 then 0.0065 x 100,000 = **650 extra deaths per 100,000 flight crew members**.

From 0.01 Sieverts/year you get a loss of 51 days per individual. A 900-hour exposure equals 0.0063 Sieverts, so the loss is 51 days x 0.0063/0.01 = **32 days per crew member.**

Problem 2 - Apollo-17 astronauts spent 22-hours in spacesuits on the lunar surface out of a 75-hour stay on the lunar surface, and a mission duration of 12 days. The total dose per astronaut was 5.5 milliSieverts. Assuming that most of the exposure came from spacesuit activity, what might be the cataract risk for future lunar explorers who may spend 3 months on the lunar surface and perhaps 3-hrs/day in spacesuits?

Answer: Scaling from the Apollo-17 exposure, the total number of hours in spacesuits might be 90 days x 3 hr/day = 270 hours. The scaled dose would be about

$$\frac{5.5 mSv}{22 hr} = \frac{X}{270 hr}$$ = **68 milliSieverts**

This exceeds the 45 milliSieverts in the 'high risk' group who have a much higher rate of cataracts by age 65.

Note: Even the Apollo-17 astronauts, with 22-hrs in spacesuits, are already in the Hi-risk group. Limiting astronaut activity to about 22-hrs for a 3-month mission is impractical, so some enhanced risk for cataracts among future lunar explorers is inevitable.

Radiation Dose and Distance

This iconic photo was taken at the Shibuya train station in Toyko on March 15, a few days after the Japan 2011 earthquake, which caused severe damage to the Fukushima Nuclear Plant in northern Japan located 250 km from Tokyo. The monitor indicates a reading of 0.6 microSeiverts per hour. The normal background dose rate is about 0.4 microSeiverts per hour.*(Courtesy Associated Press/Kyodo News)*

The devastating Japan 2011 earthquake damaged the nuclear reactors in Fukushima, which emitted clouds of radioactive gas and dust into the atmosphere. News reports indicated the radiation levels at many different locations and times through out the following week. Because radioactivity decays with time and distance, it is difficult to compare the many measurements to know if the dosages are declining as expected. The following table of measurements was collected from a variety of news reports:

Date	Distance (km)	Location	Dose Rate (microSeiverts/hr)
March 15	1 km	Fukushima #2 plant	8,200
March 15	20 km	Namai	330
March 16	30 km	Iwaki City	150
March 16	50 km	Koriyama City	2.7
March 16	70 km	Kitaibaraki City	1.2
March 16	160 km	Maebiashi City	4.0
March 15	250 km	Tokyo	0.9 maximum

Problem 1 - Graph the base-10 log of the radiation dose rate versus the base-10 log of distance from the Fukushima nuclear plant.

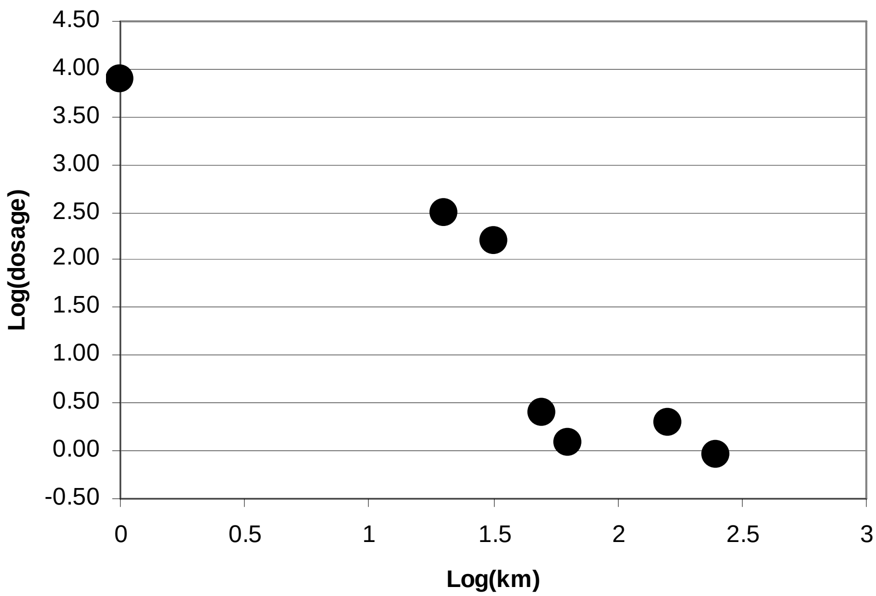
Problem 2 - On the Log-Log graph you just created, what is the approximate slope of the line that fits the data best? Show that an 'inverse-square law' has a slope of -2 on this graph.

Problem 3 - Using the graph, what would you predict for the dose rates near the city of Tamura, located 40 km from the nuclear reactors, and a position located at 10-kilometers, which is inside the limit to the evacuation zone?

Problem 1 - Graph the base-10 log of the radiation dose rate versus the base-10 log of distance from the Fukushima nuclear plant.

Distance	Dose Rate	Log(km)	Log(D)
1 km	8,200	0	3.9
20 km	330	1.3	2.5
30 km	150	1.5	2.2
50 km	2.7	1.7	0.4
70 km	1.2	1.8	0.08
160 km	4.0	2.2	0.3
250 km	0.9	2.4	-0.05

The graph of the Log(Dose Rate) and Log(distance) is as follows:

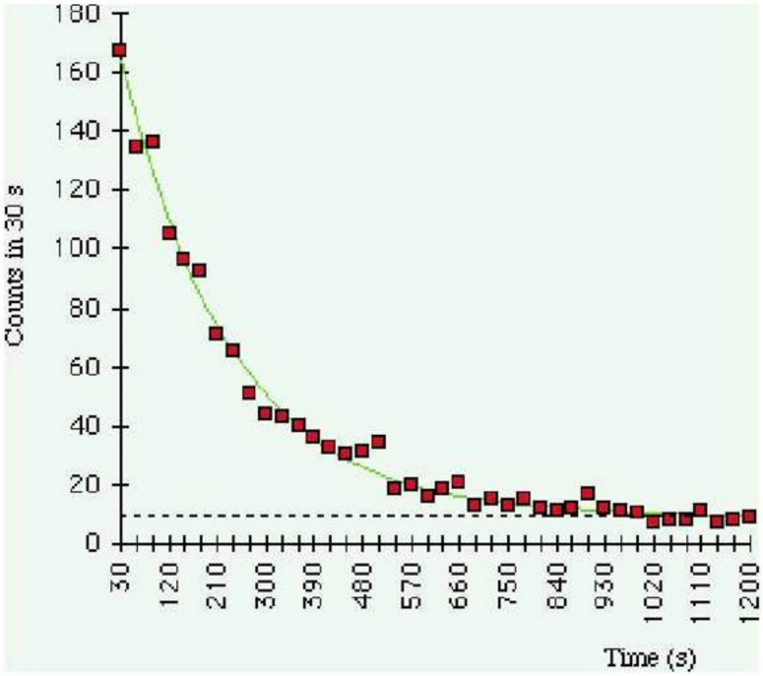


Problem 2 - On the Log-Log graph, what is the approximate slope of the line that fits the data best? Show that an 'inverse-square law' has a slope of -2 on this graph.
Answer: Using the first (0.0, 3.8) and last (2.4, -0.05) points, Slope = (-0.05 – 3.8)/(2.4 – 0.0), slope = -3.85/2.4); **Dose rate slope = -1.6**. An inverse square law is written as $y = x^{-2}$ Taking the log of both sides we get log(y) = -2 log(x). So the slope of an inverse-square law on a log-log graph would be exactly -2.0

Problem 3 – Using the graph, what would you predict for the radiation dose rates near the city of Tamura (d= 40 km), and a position located at 10-kilometers, which is inside the 20-kilometer limit to the evacuation zone?

Answer: Log(40km) = 1.6, so for x = 1.6, we can estimate from the graph that y = 1.4, and so Log(dosage) = +1.5 so that dosage = $10^{+1.5}$ = **32 microSeiverts/hour**. At a distance of 10-km, X = log(10) = 1.0 and so y = 2.0 and the dosage would be **1,000 microSeiverts/hour.**

Half-life of Ba ^{137m}



Although there are currently 94 naturally-occurring elements, the number of stable isotopes for these elements is 255. These 255 nuclei are stable in that their lifetimes are so long (in excess of 8 x 10^{24} years for tellurium-128) they cannot be reliably measured. However, only 90 of these 255 isotopes are actually stable to all forms of known radioactive decay. The remainder are eventually expected to decay, but only after a very long time!

Among the other isotopes are an additional 3100 'radioisotopes' that are known to decay after a period of time known as the half-life. Half-life is the time it takes for half of the counted atoms to change or 'decay' into some other form. The shortest known nuclear half-life is 7 x 10^{-17} seconds for the isotope beryllium-8. The longest measured half-life is for tellurium-128 which is 8 x 10^{24} years. The half-life formula is commonly given as

$$N(t) = N(0)e^{\left(-0.69\frac{t}{T}\right)}$$

where N(t) is the number of atoms or counts at time t, N(0) is the original number of atoms or counts at 'time-zero', t is the elapsed time in seconds, and T is the half-life in seconds.

Problem 1 - The graph of the barium-137m isotope decay shown above was created using a sample of barium-137m and a Geiger counter to register the number of disintegrations (counts) in 30-second intervals. From this data, and the formula for N(t), determine the half-life for barium-137m.

Barium-137m data provided by Eric Norman at EBNorman@lbl.gov.

Problem 1 – Answer

Method 1: Select any two points on the graph and note their count values and elapsed time. For example, Point 1 = (167 counts, 30 sec) and Point 2 = (22 counts, 570 sec)**.** Now create 2 equations in 2 unknowns by 'plugging in' the point coordinates into the equation and simplifying:

$$167 = N(0)e^{\left(-0.69\frac{30}{T}\right)}$$

$$22 = N(0)e^{\left(-0.69\frac{570}{T}\right)}$$

Solve the first equation for N(0) and substitute this into the second equation to eliminate N(0).

$$22 = 167e^{\left(0.69\frac{30}{T}\right)}e^{\left(-0.69\frac{570}{T}\right)}$$

Take ln of both sides and solve for T

$$Ln(22) = \ln(167) + \left(0.69\frac{30}{T}\right) - \left(0.69\frac{570}{T}\right)$$

$$3.09 - 5.11 = -\frac{372}{T}$$

So **T = 184 seconds or 3 minutes**.

Method 2: Solve directly for T:

$$22 = 167e^{-0.69\left(\frac{540}{T}\right)} \quad \text{so} \quad 22 = 167e^{\left(\frac{-372.6}{T}\right)} \quad \text{then} \quad ln22 = \ln 167 - \frac{372.6}{T}$$

$$\text{so} \quad 3.09 = 5.12 - \frac{372.6}{T} \quad \text{then} \quad T = \frac{-372.6}{3.09 - 5.12} \quad \text{and so } T = 183.7 \text{ seconds}$$

The actual half-life is 153 seconds.

Note: Barium-137m is produced by the decay of Cesium-137, which is used for medical imaging. Barium-137m, when first formed, is in an excited state, which decays to its 'ground state' by emitting a single gamma ray photon with an energy of 662 keV.

The devastating earthquake that struck northern Japan on March 10, 2011 also caused several of the nuclear reactors at the Fukushima Nuclear Plant to explosively vent radioactive gas and dust clouds into the environment.

Although the initial radiation levels were extremely high, the natural decay of the radioactive compounds will cause the radiation levels at any given distance to steadily reduce in intensity.

The most common radioisotopes that are likely to be involved in the vented gases are Cesium-137 and Iodine-131. These will become incorporated into atmospheric dust grains and fall to the ground, contaminating the soil. Cesium-137 has a half-life of 30 years, while Iodine-131 has a half-life of 8 days. This means that, for example, if you measured the dose you get from a sample of Iodine-131, after 8 days, the dose rate will have dropped to 1/2 its original level on Day-1. After 16 days it will be 1/4 of its original level on Day-1, and so on.

The formula for half life and radiation dose rate is:

$$D(t) = D(0)e^{\left(-0.69\frac{t}{T}\right)}$$

where D(0) is the dose rate on Day-0, D(t) is the dose rate on Day-t, and T is the half-life in days.

Problem 1 - The natural background radiation dose rate is about 3.5 milliSeiverts/year. What is this natural radiation dose rate in microSeiverts/hour?

Problem 2 - On Friday, March 18, *NHK News*, the online news service for Japan ,reported that Japan's Science Ministry had posted new radiation measurements. The Ministry indicated that at a location 30 km northwest of the Fukushima Daiichi nuclear plant, the radiation dose rates were 170 microSeiverts/hour on March 17, and 150 microSeiverts/hour on March 18. Assuming that the decrease is entirely caused by the decay of a radioisotope, A) what is the half-life of this isotope in days? B) What is the likely candidate for the radioisotope that is causing most of the radiation at this location?

Problem 1 - The natural background radiation dose rate is about 3.5 milliSeiverts/year. What is this natural radiation dose rate in microSeiverts/hour?

Answer; 3.5 milliSeiverts/year x (1000 micros/1 milli) x (1 year/365 days) x (1 day/24 hours) = **0.4 microSeiverts/hour**.

Problem 2 - On Friday, March 18, *NHK News*, the online news service for Japan ,reported that Japan's Science Ministry had posted new radiation measurements. The Ministry indicated that at a location 30 km northwest of the Fukushima Daiichi nuclear plant, the radiation dose rates were 170 microSeiverts/hour on March 17, and 150 microSeiverts/hour on March 18. Assuming that the decrease is entirely caused by the decay of a radioisotope, A) what is the half-life of this isotope in days? B) What is the likely candidate for the radioisotope that is causing most of the radiation at this location?

Answer: A) From the information given, and the formula for D(t) we have D(0) = 170, t = 1 day, D(1) = 150, we solve:P

$$150 = 170e^{\left(-0.69\frac{1day}{T}\right)}$$

$$\frac{150}{170} = e^{\left(-0.69\frac{1day}{T}\right)}$$

$$0.882 = e^{\left(-0.69\frac{1day}{T}\right)}$$ now take the natural-log of both sides

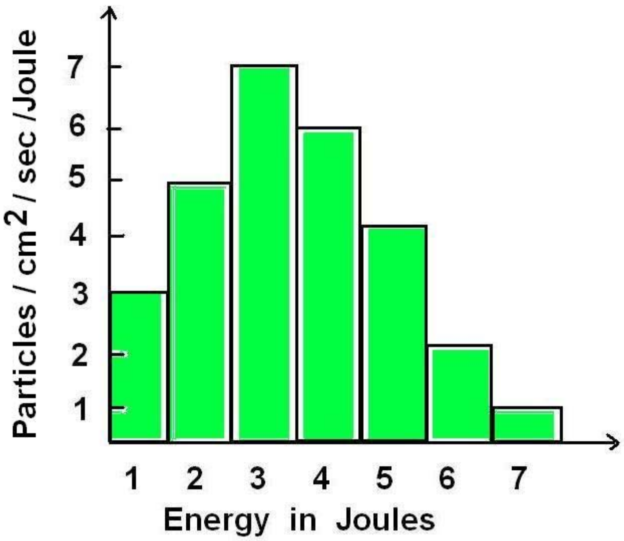
$$\ln(0.882) = -0.69\frac{1day}{T}$$ so $$-0.126 = -0.69\frac{1day}{T}$$

then $T = \frac{0.69}{0.126}$

so **T = 5.5 days is the half-life for the decay in the dose rate.**

B) **The most likely candidate contributing to the radiation exposure at this location is Iodine-131, which has a half-life of 8 days.**

Note to Teacher: For an internal dose, the (cumulative) dose increases over time until about 7 half-lives have elapsed. The dose rate will decrease as will the number of I-131 atoms in the patient and the count rate near the patient.



Because particles and radiation can possess a wide range of energies, it is often not enough to just measure the flux at one energy to completely describe the particles or radiation. Physicists measure the 'spectrum' of particles and radiation to learn more about how they are produced.

The above bar graph shows the spectrum of hypothetical particles detected in space. They are binned by the amount of energy they carry in units of Joules. The vertical axis indicates the numbers of particles detected that passed through a square-centimeter of surface in one second in an energy interval of exactly 1 Joule.

Problem 1 – In the above graph, at what energy do most of the particles occur?

Problem 2 - What is the energy range of the particles on the graph?

Problem 3 - Each bin in the spectrum has an energy interval of one Joule. What are the units of the area of each bin?

Problem 4 - Over the full energy range of this spectrum, how many particles would you count in 5 seconds, with a detector that has an area of 10 cm^2?

Problem 1 - In the above graph, at what energy do most of the particles occur?

Answer: The peak of the spectrum occurs for particles at an energy of **3 Joules**.

Problem 2 - What is the energy range of the particles on the graph?

Answer: The range extends from **1 Joule to 7 Joules**.

Problem 3 - Each bin in the spectrum has an energy interval of one Joule. What are the units of the area of each bin?

Answer: The height of each rectangular bar is in units of particles/cm^2/sec/Joules. The width of each bin is 1 Joule, so the product of these units is just **partices/cm^2/sec**, which is the particle flux.

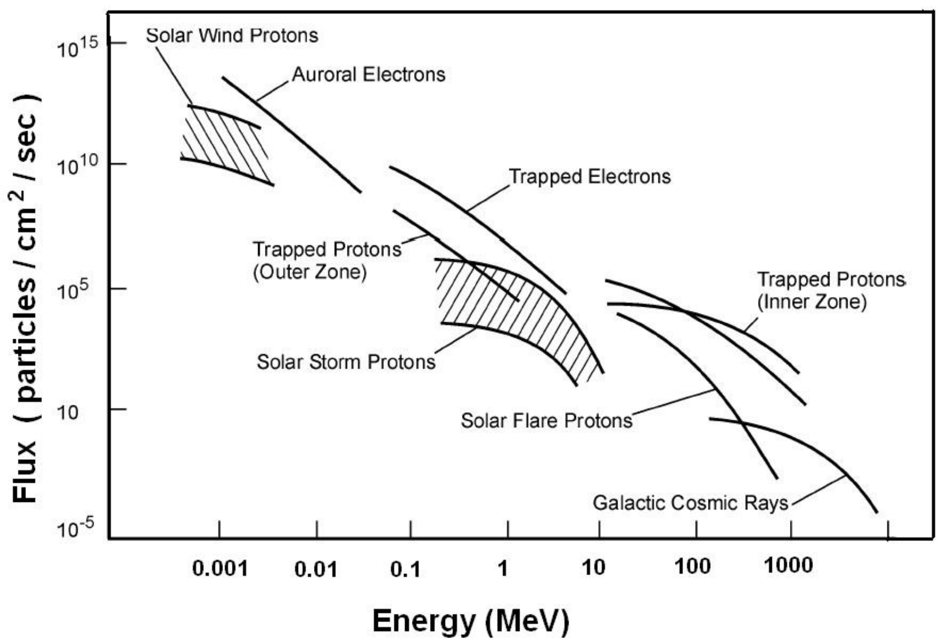
Note to Teacher: Another name for the vertical axis is therefore the particle spectral energy density. The term 'density' is used here to describe the number of particles of a specific energy 'packed' into an energy interval of 1 Joule. It is analogous to the more conventional usage of the term density to refer to the number of kilograms of matter 'packed' into a volume of 1 cubic meter.

Problem 4 - Over the full energy range of this spectrum, how many particles would you count in 5 seconds, with a detector that has an area of 10 cm^2?

Answer: Each bin is 1 Joule wide, so the flux contributed by the particles in each energy bin is just the bin value. Add up all of the bins to get the total particle flux: 3 + 5 + 7 + 6 + 4 + 2 + 1 = 27 particles/cm^2/sec/Joule x (1 Joule/bin) = 27 particles/cm^2/sec.

Now multiply this flux by the detector area and time:
N = 27 particles/cm^2/sec x (10 cm^2) x (5 seconds)
= **1350 particles**.

The Space Radiation Particle Spectrum



Decades of investigations using a variety of ground, air and space-based sensors have established the energy spectrum of particles in the Earth's space environment. Some of these, such as the auroral electrons, solar storm protons and solar flare protons, have fluxes that vary depending on the level of solar activity. Others such as the trapped electrons and protons of the van Allen Belts, and galactic cosmic rays are relatively constant in time.

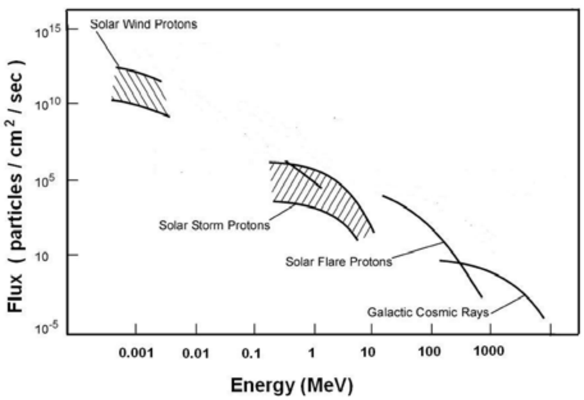
Because the energies and fluxes for the various particles spans such a vast range, it is common to represent particle spectra on Log-Log plots such as the one above. For example, Trapped Protons in the Outer Van Allen belts with energies of 1 Me V ('1' on the horizontal axis) have a typical average flux of about 10^5 particles/cm^2/sec ('10^5' on the vertical axis). The intensity (or flux) of these particles depends on your location in space.

Problem 1 - Suppose a satellite operates in geosynchronous orbit just outside the majority of the van Allen Belts. What would be the likely types of particles the satellite would encounter in this environment? (Note: Auroral electrons are found below the van Allen Belts)

Problem 2 - A GPS satellite designer wants to design the proper shielding for sensitive electronics operating inside the van Allen Belt zone. In the energy range from 0.1 MeV to 10 MeV, and to the nearest power of 10, about what would be the predicted ratio of Trapped Protons to shield against in this energy range?

Energy spectrum obtained from 'Radiobiology for Space Research', Isabelle Testard, Laure Sabatier, Sylvia Ritter, Marco Durante and Gerhard Kraft, Nuclear Physics European Collaboration Committee (NUPECC), adapted from J. W. Wilson et al., 'Transport Methods and Interaction for Space Radiation', NASA 1991, Publication 1257. (www.nupecc.org/iai2001/report/B42.pdf)

Problem 1 - Suppose a satellite operates in geosynchronous orbit just outside the majority of the van Allen Belts. What would be the likely types of particles the satellite would encounter in this environment? Answer: See figure below.



Problem 2 - A GPS satellite designer wants to design the proper shielding for sensitive electronics operating inside the van Allen Belt zone. In the energy range from 0.1 MeV to 10 MeV, and to the nearest power of 10, about what would be the predicted ratio of Outer Zone to Inner Zone Trapped Protons to shield against in this energy range?

Answer: The Space Radiation Particle Spectrum indicates that at an energy of 0.1 MeV, Trapped Protons (Outer Zone) have a flux of about 10^7 particles/cm^2/sec. At 10 MeV, the Trapped Protons (Inner Zone) have a flux of about 10^5 particles/cm^2/sec. The ratio is about **100:1**. There are about 100 times more low-energy Outer Zone protons to shield against than the high-energy Inner Zone protons.

Radiation Dose Rates at Airline Flight Altitude

In flight there are two principal sources of natural radiation to consider: Galactic Cosmic Rays (GCR) which are always present, and Solar Proton Events (SPE), sometimes called Solar Cosmic Ray (SCR) events, which occur sporadically. GCR provide an inescapable radiation background which varies over the solar cycle of about 11 years. GCR are maximum when solar activity is minimum and vice-versa. The resulting dose equivalent at aircraft also varies quite strongly with altitude and latitude.

The following table provides estimates of the radiation dose equivalent in microSieverts/hr at the times of sunspot minimum and sunspot maximum obtained through the use of the CARI-6 program developed by the Civil Aeromedical Institute of the Federal Aviation Administration.

Altitude (feet)	Sunspot Minimum (microSv/hr)		Sunspot Maximum (microSv/hr)	
	$+35^o$ North	$+70^o$ North	$+35^o$ North	$+70^o$ North
0	0.04	0.04	0.04	0.04
10,000	0.19	0.21	0.17	0.18
20,000	0.98	1.14	0.88	0.95
30,000	3.25	4.06	2.85	3.24
40,000	6.78	9.02	5.88	6.99
50,000	9.71	13.8	8.36	10.3
60,000	11.1	17.1	9.49	12.3
70,000	11.4	19.2	9.68	13.3
80,000	11.2	20.6	9.44	13.8

Problem 1 - A typical round-trip flight from New York City to San Francisco (latitude 35^o North, altitude 40,000 feet) takes about 12 hours. What is the total dose in microSieverts that a passenger would accumulate in this time during A) sunspot maximum? B) Sunspot minimum?

Problem 2 - From all natural sources, the typical ground-level dose rate is about 0.4 microSieverts/hr. How many additional days on the ground would be required to absorb the same radiation dose as a passenger receives during sunspot maximum for the trip in Problem 1?

Problem 3 - Air crews often travel 900 hours each year at flight altitudes. If the average dose rate at this altitude is about 7.2 microSieverts/hr: A) What is the average total dose received in microSieverts for 900 hours? B) How many days on the ground would it take to accumulate the same annual dose from flying in a passenger jet as a member of the flight crew…or frequent flyer?

Problem 1 - A typical round-trip flight from New York City to San Francisco (latitude 35^{o} North, altitude 40,000 feet) takes about 12 hours. What is the total dose in microSieverts that a passenger would accumulate in this time during A) sunspot maximum? B) Sunspot minimum?

Answer; The table indicates a dose rate of 6.78 microSieverts/hr during sunspot minimum and 5.88 microSieverts/hr during sunspot maximum. The total absorbed dose would be A) 6.78 x 12 = **81.4 microSieverts** and B) 5.88 x 12 = **70.6 microSieverts**

Problem 2 - From all natural sources, the typical ground-level dose rate is about 0.4 microSieverts/hr. How many additional days on the ground would be required to absorb the same radiation dose as a passenger receives during sunspot maximum for the trip in Problem 1?

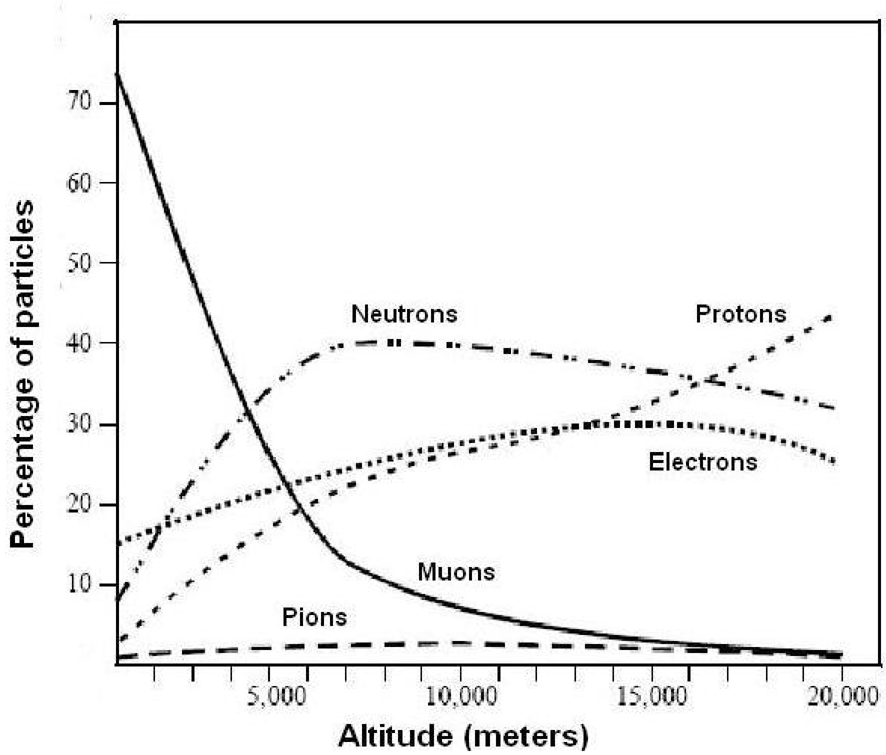
Answer: Ground dose rate is 0.4 microSieverts/hr, so 81.4 microSieverts would be absorbed in about 204 hours or 8.5 days!

Problem 3 - Air crews often travel 900 hours each year at flight altitudes. If the average dose rate at this altitude is about 7.2 microSieverts/hr: A) What is the average total dose received in milliSieverts for 900 hours? B) How many days on the ground would it take to accumulate the same annual dose from flying in a passenger jet as a member of the flight crew…or frequent flyer?

Answer; A) 7.2 microSeiverts/hr x 900 hrs of flight yields = **6.48 milliSieverts**.

B) The ground-level dose rate is about 0.4 microSieverts/hr so for 24 hours the 'normal' dose would be 9.6 microSieverts/day. The 900-hours per annum flying is equivalent to 6480/9.6 = **765 days of additional exposure**.

Actually, had the crew member remained on the ground they would have received 900-hrs x 0.4 microSieverts/hr = 360 microSieverts, so the <u>additional</u> radiation from flying is 6480 - 360 = 6120 microSieverts, or an equivalent of 638 days additional radiation.



The graph above shows how the types of cosmic ray particles changes from ground level to typical 15,000-meter altitudes at which commercial aircraft are flown. The original cosmic rays are primarily high-energy protons, neutrons and electrons, however when they collide with atmospheric nuclei of oxygen and nitrogen, they produce nuclear interactions that yield pions (pi mesons), which then decay to become muons at lower altitudes.

Problem 1 - At what altitude would you expect to find approximately equal numbers of electrons, protons and neutrons?

Problem 2 - A scientist wants to measure the muon flux from the top of Mt Everest (about 9,000 meters). What percentage of cosmic ray particles would he expect to detect at this elevation that were actually muons?

Problem 3 - A commercial radiation dosimeter is designed to detect only the ground-level muon particles that contribute to our daily natural cosmic ray background of about 0.5 microSieverts/hr. Suppose a passenger brought this dosimeter on board a trans-Atlantic flight from Boston to Paris (altitude of 15,000 meters) to measure her dose rate as a passenger. Explain why the readings would not give a proper indicator of her actual radiation exposure.

The graph was adapted from the journal article: *'Atmospheric cosmic rays and solar particles at aircraft altitudes'* by K. O'Brien, et al., published in the journal Environmental Institute, Supplement 1: S9-S44, 1996.

Problem 1 - At what altitude would you expect to find approximately equal numbers of electrons, protons and neutrons?

Answer: **At 16,000 meters**, N = 35%, p = 35% and E = 30%.

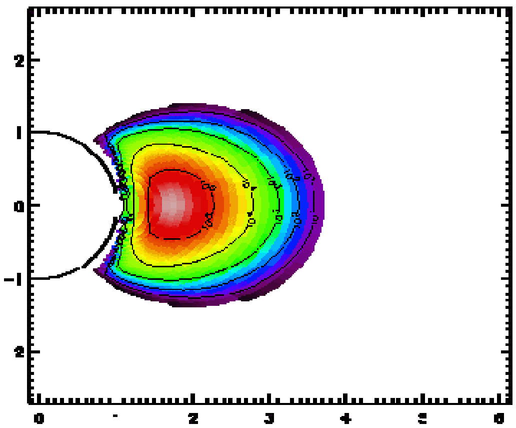
Problem 2 - A scientist wants to measure the muon flux from the top of Mt Everest (about 9,000 meters). What percentage of cosmic ray particles would he expect to detect at this elevation that were actually muons?

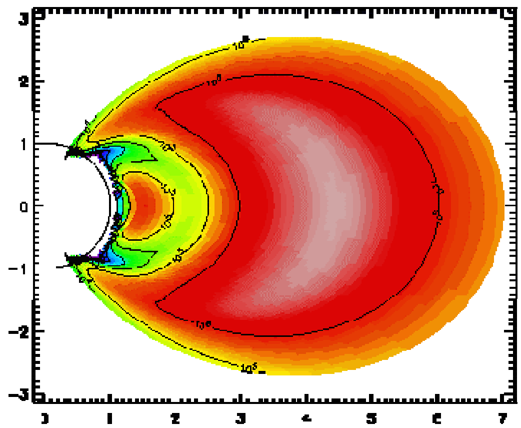
Answer; From the graph, at 9,000 meters the muons only represent about **10% or 1 in 10 of the particles detected.**

Problem 3 - A commercial radiation dosimeter is designed to detect only the ground-level muon particles that contribute to our daily natural cosmic ray background of about 0.5 microSieverts/hr. Suppose a passenger brought this dosimeter on board a trans-Atlantic flight from Boston to Paris to measure her dose rate as a passenger. Explain why the readings would not give a proper indicator of her actual radiation exposure.

Answer: At typical jet altitudes of 15,000 meters, the dosimeter would detect very few muons and give a low measurement of the radiation dose. The largest number of cosmic ray particles at this altitude are the neutrons, protons and electrons, which are not detected, but which will produce radiation exposure and contribute to the dose rate measured.

Estimating the Density of the van Allen Belts





The van Allen Belts were discovered in ca 1958 when the Explorer 1 and 3 satellites, equipped with Geiger counters, detected clouds of 'radioactivity' within 50,000 km of Earth. Substantial research eventually identified four components: Two Inner Belts, consisting of high-energy electrons (~100 keV) and protons (100 keV to 400 MeV); an Outer Belt consisting of primarily high-energy (0.1 to 10 MeV) electrons; and a generally-empty Slot Region separating these two particle systems.

Unlike other physical systems such as Earth's atmosphere at sea-level (1.29 kg/m^3) or even the solar wind (5 $atoms/cm^3$), the density of the van Allen Belts is not very well defined. The numbers of particles present at any one moment varies by orders of magnitude depending on the particle type (electrons or protons), their energies (1 keV to 400 MeV), and the level of solar activity.

Two quantities that can be measured are the average speed of the particles and their flux. Flux is a measure of the number of particles passing through a square centimeter of surface each second. Dividing the average particle flux by the average particle speed yields the density of the particles in space.

The figures above show the fluxes of the protons (left) and electrons (right) colorized by their respective fluxes. The most common particles in the Inner Belt consists of low-energy electrons (Flux ~10^6 particles/cm^2/sec) and high-energy protons (Flux ~10^5 particles/cm^2/sec). In the Outer Belt, mostly high-energy electrons are present (Flux ~ 10^6 particles/cm^2/sec).

Problem 1 - Show that in terms of the units for each of the quantities, that Density = Flux / Speed.

Problem 2 - If the (E = 100 keV) electrons and (E=10 MeV) protons travel at speeds of about 1.8×10^{10} cm/sec and 4.4×10^9 cm/sec respectively, what is the average density of the Inner Belt electrons and protons?

Problem 3 - If the (E = 1 MeV) electrons travel at speeds of about 2.6×10^{10} cm/sec, what is the average density of the Outer Belt electrons?

The figures are based upon the NASA / SPENVIS AE-8 and AP-8 models for the particle environment near Earth.
(see: http://www.spenvis.oma.be/help/background/traprad/traprad.html)

Problem 1 - Show that in terms of the units for each of the quantities, that Density = Flux / Speed. Answer:

$$Flux = \frac{particles}{cm^2 \sec}$$

$$Speed = \frac{cm}{\sec}$$

$$Density = \frac{\left(\frac{particles}{cm^2 \sec}\right)}{\left(\frac{cm}{\sec}\right)}$$

$$Density = \left(\frac{particles}{cm^2 \sec}\right) x \left(\frac{\sec}{cm}\right)$$

$$Density = \frac{particles}{cm^3}$$

Problem 2 - If the (E = 100 keV) electrons and (E=10 MeV) protons travel at speeds of about 1.8×10^{10} cm/sec and 4.4×10^9 cm/sec respectively, what is the average density of the Inner Belt electrons and protons?

Answer: Inner Electron Belt:

Density = (10^6 electrons/cm^2/sec) / (1.8×10^{10} cm/sec)

= **5.6×10^{-5} electrons/cm^3**.

Inner Proton Belt:

Density = (10^5 protons/cm^2/sec) / (4.4×10^9 cm/sec)

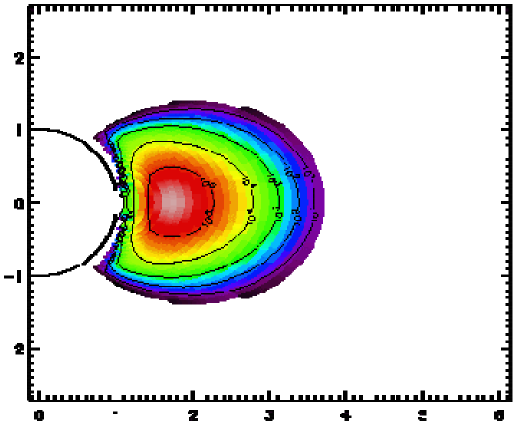
= **2.3×10^{-5} particles/cm^3**.

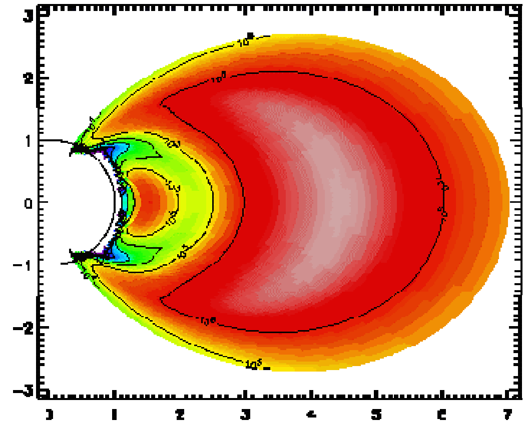
Problem 3 - If the (E = 1 MeV) electrons travel at speeds of about 2.6×10^{10} cm/sec, what is the average density of the Outer Belt electrons?

Answer: Outer Electron Belt:

Density = (10^6 electrons/cm^2/sec) / (2.6×10^{10} cm/sec)

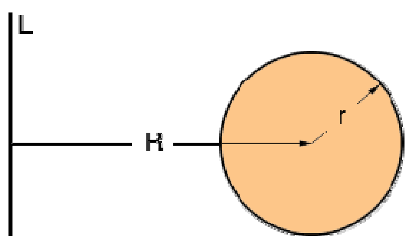
= **3.8×10^{-5} electrons/cm^3**.





The van Allen Belts were discovered in 1958 when the Explorer 1 and 3 satellites, equipped with Geiger counters, detected clouds of 'radioactivity' within 50,000 km of Earth. Substantial research eventually identified four components: Two Inner Belts, consisting of low-energy electrons (~100 keV) and higher-energy protons (100 keV to 400 MeV); an Outer Belt consisting of primarily high-energy (0.1 to 10 MeV) electrons; and a generally-empty Slot Region separating these two particle systems.

The figures above show the fluxes of the protons (left) and electrons (right) colorized by their respective fluxes. The most common particles in the Inner Belt consists of low-energy electrons (Flux ~10^6 particles/cm^2/sec) and high-energy protons (Flux ~10^5 particles/cm^2/sec). In the Outer Belt, mostly high-energy electrons are present (Flux ~ 10^6 particles/cm^2/sec). The units along the x and y-axis are given in multiples of Earth's radius so that '1' = 6378 km.



Problem 1 - We will approximate the volumes of the Inner and Outer van Allen Belts as toroidal figures centered on Earth. (A torus is formed by rotating a circle with a radius of r, around an axis L located at a distance of R from the center of the circle). Show that the formula for the volume of a torus shown in the cross-section above is given by the formula

$$V = 2\pi^2 R r^2$$

Problem 2 - What would you estimate for the volume, in cubic meters, of A) The Inner Proton Belt? B) The Inner Electron Belt? and C)The Outer Electron Belt?

The figures are based upon the NASA / SPENVIS AE-8 and AP-8 models for the particle environment near Earth.
(see: http://www.spenvis.oma.be/help/background/traprad/traprad.html)

Problem 1 - We will approximate the volumes of the Inner and Outer van Allen Belts as toroidal figures centered on Earth. Show that the formula for the volume of a torus shown in the cross-section above is given by the formula

$$V = 2\pi^2 R r^2$$

Answer: the circumference of the torus is just $C = 2\pi R$ .The cross-section has an area of $A = \pi r^2$, so the volume of this cylinder with a height of C and a base area of A is just $V = A \times C$ so $V = 2\pi^2 R r^2$ as stated.

Problem 2 - What would you estimate for the volume, in cubic meters, of A) The Inner Proton Belt? B) The Inner Electron Belt? and C)The Outer Electron Belt?

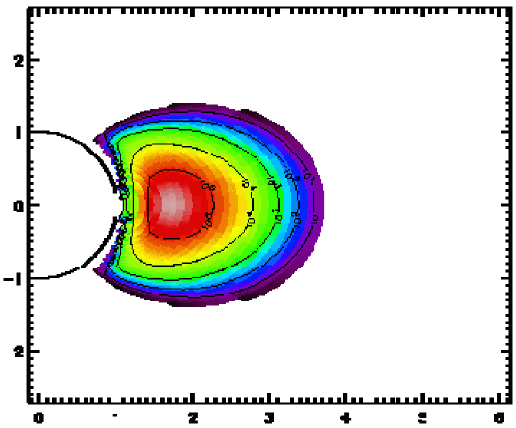
Answer: From the two figures, we can estimate the following quantities:

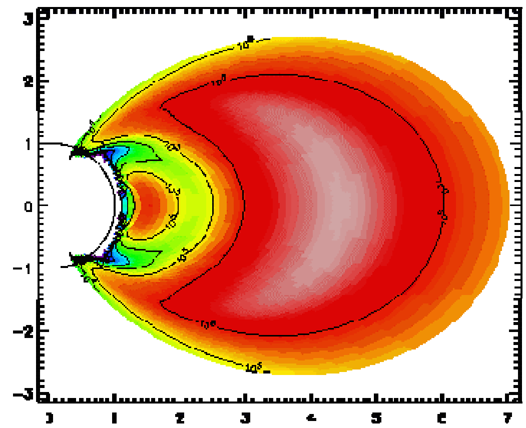
A) The Inner Proton Belt
R = 2.2 x 6378 km   r = 1 x 6378 km
= 14,000 km   = 6378 km
So Volume = $2 (3.14)^2 (14000 \text{ km}) (6378 \text{ km})^2$
= 1.1×10^{13} km^3
= **1.1×10^{22} m^3**

B) The Inner Electron Belt
R = 1.5 x 6378 km   r = 0.5 x 6378 km
= 9,600 km   = 3,200 km
So Volume = $2 (3.14)^2 (9{,}600 \text{ km}) (3{,}200 \text{ km})^2$
= 1.9×10^{12} km^3
= **1.9×10^{21} m^3**

C)The Outer Electron Belt
R = 4.5 x 6378 km   r = 2 x 6378 km
= 29,000 km   = 13,000 km
So Volume = $2 (3.14)^2 (29000 \text{ km}) (13000 \text{ km})^2$
= 9.7×10^{13} km^3
= **9.7×10^{22} m^3**

Estimating the Mass of the van Allen Belts





The van Allen Belts were discovered in ca 1958 when the Explorer 1 and 3 satellites, equipped with Geiger counters, detected clouds of 'radioactivity' within 50,000 km of Earth. Substantial research eventually identified four components: Two Inner Belts, consisting of high-energy electrons (~100 keV) and protons (100 keV to 400 MeV); an Outer Belt consisting of primarily high-energy (0.1 to 10 MeV) electrons; and a generally-empty Slot Region separating these two particle systems.

The figures above show the fluxes of the protons (left) and electrons (right) colorized by their respective fluxes. The most common particles in the Inner Belt consists of low-energy electrons (Flux ~10^6 particles/cm^2/sec) and high-energy protons (Flux ~10^5 particles/cm^2/sec). In the Outer Belt, mostly high-energy electrons are present (Flux ~ 10^6 particles/cm^2/sec). The units along the x and y-axis are given in multiples of Earth's radius so that '1' = 6378 km.

The density and volume of the van Allen belts can be estimated from the data given in the above figure assuming that the belts are in the shape of concentric tori centered on Earth, and the particles densities can be derived from the respective particle fluxes divided by the average particle speeds for the electrons and protons. The mass of an electron is just 9.1 x 10^{-31} kg, and a proton has a mass of 1.7 x 10^{-27} kg.

Problem 1 - For the Inner Proton Belt, the estimated density is N = 2.3 x 10^{-5} protons/cm^3. The volume of this belt is approximately V = 1.1 x 10^{22} m^3. Approximately what is the mass of this belt in kilograms?

Problem 2 - For the Inner Electron Belt, the estimated density is N = 5.6 x 10^{-5} protons/cm^3. The volume of this belt is approximately V = 1.9 x 10^{21} m^3. Approximately what is the mass of this belt in kilograms?

Problem 3 - For the Outer Electron Belt, the estimated density is N = 3.8 x 10^{-5} protons/cm^3. The volume of this belt is approximately V = 9.7 x 10^{22} m^3. Approximately what is the mass of this belt in kilograms?

The figures are based upon the NASA / SPENVIS AE-8 and AP-8 models for the particle environment near Earth.
(see: http://www.spenvis.oma.be/help/background/traprad/traprad.html)

Problem 1 - For the Inner Proton Belt, the estimated density is N = 2.3×10^{-5} protons/cm^3. The volume of this belt is approximately V = 1.1×10^{22} m^3. Approximately what is the mass of this belt in kilograms?

Answer: mass = density x volume x mass/particle so
$M = (2.3 \times 10^{-5} \text{ protons/cm}^3)(1.1 \times 10^{22} \text{ m}^3)(1.7 \times 10^{-27} \text{ kg})(10^6 \text{ cm}^3/1 \text{ m}^3)$
= **0.00043 kg**

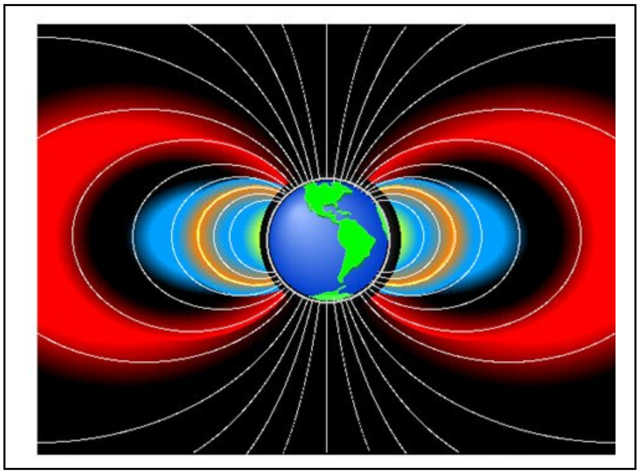
Problem 2 - For the Inner Electron Belt, the estimated density is N = 5.6×10^{-5} protons/cm^3. The volume of this belt is approximately V = 1.9×10^{21} m^3. Approximately what is the mass of this belt in kilograms?

Answer: mass = density x volume x mass/particle so
$M = (5.6 \times 10^{-5} \text{ electrons/cm}^3)(1.9 \times 10^{21} \text{ m}^3)(9.1 \times 10^{-31} \text{ kg})(10^6 \text{ cm}^3/1 \text{ m}^3)$
= **9.7×10^{-8} kg**.

Problem 3 - For the Outer Electron Belt, the estimated density is N = 3.8×10^{-5} protons/cm^3. The volume of this belt is approximately V = 9.7×10^{22} m^3. Approximately what is the mass of this belt in kilograms?

Answer: mass = density x volume x mass/particle so
$M = (3.8 \times 10^{-5} \text{ electrons/cm}^3)(9.7 \times 10^{22} \text{ m}^3)(9.1 \times 10^{-31} \text{ kg})(10^6 \text{ cm}^3/1 \text{ m}^3)$
= **3.3×10^{-6} kg**.

Note: The total mass of the van Allen Belts is about 4.3×10^{-4} kg or 0.4 grams, and dominated by the Inner Proton Belt.



The van Allen Radiation Belts surround Earth in the equatorial plane. Satellites and humans are exposed to varying dose rates of radiation as they move along orbits of differing inclination and altitude. These variations can be mathematically modeled given the details of the location, extent, and density of the various particle populations surrounding Earth in space. The results from one such calculation is shown in the table below.

Orbit Altitude (km)	Inclination Angle of the Orbit Plane (degrees)			
	0	45	65	90
300	**0.05**	**0.05**	**0.05**	**0.05**
500	**0.16**	**0.16**	**0.16**	**0.16**
1000	**2.00**	**0.90**	**0.65**	**0.58**
2500-3500	**110.00**	**26.00**	**20.00**	**18.00**
7500	**2.60**	**3.40**	**2.60**	**2.40**

Note: Radiation dose rates (bold) are from protons in the Inner van Allen Belt, with units given in Sieverts/day. Dose rates calculated for no shielding. Data from Grigoriev (1975).

Problem 1 - The Space Shuttle and International Space Station remain at altitudes near 300 km. If the normal stay on the ISS is 90 days in an orbit inclined by 52^o, and the typical shielding from the space station walls provided a reduction of about 50-times, what is the A) daily radiation dose? B) total mission dose?

Problem 2 - A manned spacecraft is launched on a trajectory that has an inclination angle of 45^o, and that takes 10 minutes to travel through each of the 5 distance zones shown in the table. What is the total dose, in Sieverts and in Rems, accumulated by an astronaut on such a journey if the spacecraft shielding was comparable to the ISS? (1 Rem = 0.01 Sieverts).

Problem 1 - The Space Shuttle and International Space Station remain at altitudes near 300 km. If the normal stay on the ISS is 90 days in an orbit inclined by 52^o, and the typical shielding from the space station walls provided a reduction of about 50-times, what is the A) daily radiation dose? B) total mission dose?

Answer: A) The unshielded dose rate is 0.05 Sieverts/day or 50 milliSieverts/day**.** With the typical wall shielding, the actual interior rate is about **1 milliSievert/day.**

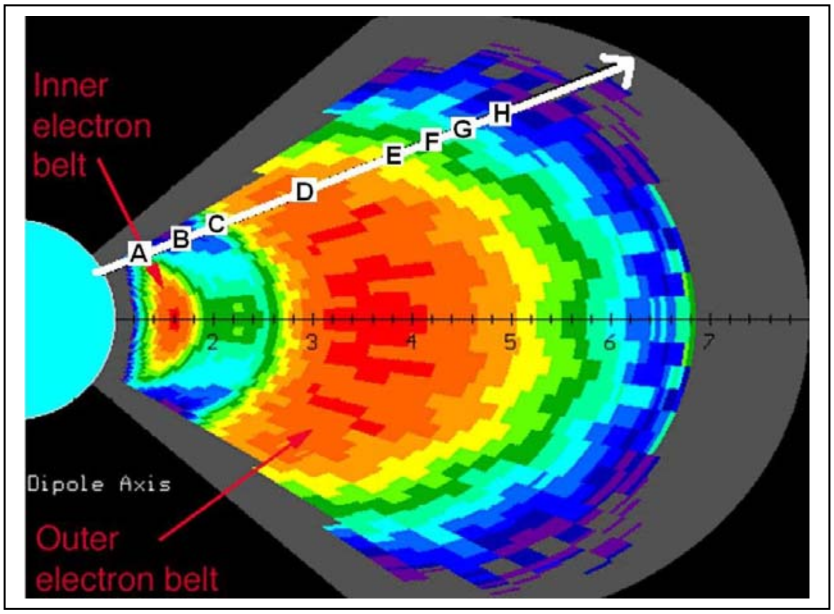
B) The total 90-day mission dose is
D = 90 days x 1 milliSievert/day
= **90 milliSieverts**.

Problem 2 - A manned spacecraft is launched on a trajectory that has an inclination angle of 45^o, and that takes 10 minutes to travel through each of the 5 distance zones shown in the table. What is the total dose, in Sieverts and in Rems, accumulated by an astronaut on such a journey if the spacecraft shielding was comparable to the ISS? (1 Rem = 0.01 Sieverts)

Answer: The unshielded dose rates are in Sieverts/day, so 10 minutes is 0.007 days. Then the total unshielded dose is just D = (0.05 + 0.16 + 0.9 + 26 + 3.4)x 0.007 = 0.21 Sieverts or 21 Rems. With a shielding reduction of 50-times, the actual interior dose is about **4.2 milliSieverts** or **0.42 Rems**.

Note: The typical absorbed dose for radiation on the ground is 0.3 Rem each year, so this 50-minute passage through space was equal to 0.42/0.3 = 1.4 years of normal exposure on the ground!

It is commonly believed that the van Allen 'radiation belts' encircling Earth are deadly to astronauts passing through them. We can put this assertion to a test buy suing actual data from satellites that operate in these regions of near-Earth space. The figure below was developed by Dr. Joe Fennel (Aerospace Corporation) based on data from NASA's Combined Release and Radiation Effects (CRRES) satellite launched in 1990.



The red colors represent regions where the unshielded dose would be about 2 Sieverts/hr, while the blue regions would result in lower doses of 10 milliSieverts/hr. The out-going Apollo missions traveled through this region on a typical 1-hour path that grazed the top edge of the belts along the indicated trajectory. The unshielded dose rates are estimated for the regions A to H in the table below:

Region	Duration (minutes)	Dose rate (milliSieverts/hr)	Total Dose (Sieverts)
A	5	216	
B	8	36	
C	3	144	
D	20	360	
E	5	252	
F	3	72	
G	4	29	
H	12	7	

Problem 1 - What is the total dose in Sieverts for each segment of the trip, and for the entire trip assuming the outgoing and ingoing trajectories are similar?

Problem 2 - The astronauts were in the Command Module, which reduced the radiation exposure by about 40 times. What is the round-trip dose accumulated by the astronauts?

Problem 1 - What is the total dose in Sieverts for each segment of the trip, and for the entire trip assuming the outgoing and ingoing trajectories are similar?

Region	Duration (minutes)	Dose rate (milliSieverts/hr)	Total Dose (Sieverts)
A	5	216	0.018
B	8	36	0.0048
C	3	144	0.0072
D	20	360	0.12
E	5	252	0.021
F	3	72	0.0036
G	4	29	0.0019
H	12	7	0.0014

For example: Region A: 5 minutes = 0.083 hours, then 216 milliSieverts/hr x 0.083 hr = 0.018 Sieverts.

The outgoing trip total, based on the sum of the totals for each segment in column 4, was about 0.18 Sieverts. For the full round-trip, lasting 2 hours, it was **0.36 Sieverts**.

Problem 2 - The astronauts were in the Command Module, which reduced the radiation exposure by about 40 times. What is the round-trip dose accumulated by the astronauts?

Answer: The 1-hour unshielded trip had a dose rate of 180 milliSieverts/hour. With shielding this became 180 mSv/hr x (1/40) = 5 milliSv/hr, so for the full 2-way trip, the total dose was **10 milliSieverts.**

By comparison, the ground-level natural background rate is about 4 milliSv/year. A better comparison is the hourly ground-level rate in North America of about 0.45 microSieverts/hour, so the VARB shielded rate is about 22,000 times higher! Fortunately this exposure was for only a brief time, and so the total radiation <u>accumulated</u> by the astronauts was very small!

Total Dose (Rem)	Medical Impact
5000	Predicted dose from a Carrington Superstorm in a spacesuit (1 gm/cm2 shielding) in deep space
500	100% lethal dose for humans in 30 days.
400	Predicted dose from the August 1972 flare in a spacesuit.
200	Predicted dose from a Carrington Superstorm with 10 gm/cm2 shielding in deep space
100	About 5 out of every 100 people will experience a fatal cancer at this dose level if delivered over a short time (minutes to hours)
50	Radiation absorbed by spacesuited astronauts from January 15, 2005 solar flare
40	Predicted one-year cosmic ray dose in interplanetary space during sunspot minimum with shielding
30	Estimated dose from February 1956 solar proton event with 20 gm/cm2 shielding
29	Predicted dose from a Carrington Superstorm with 20 gm/cm2 shielding at ISS altitudes (400km)
25	A typical lifetime accumulated radiation dose for person living on the surface of Earth.
20	Maximum measured, unshielded radiation dosage per year on the surface of Mars
15	Estimated dose from August 1972 solar proton event with 20 gm/cm2 shielding
10	Predicted one-year cosmic ray dose in interplanetary space during sunspot maximum with shielding
5.0	Lowest annual dose for which no increases average human cancer rates have been detected.
3.0	Radiation dose for a 90-day stay in the International Space Station during average space weather conditions
2.0	Radiation dose for Apollo Astronauts visiting the moon and returning to Earth
1.0	Radiation dose absorbed by ISS astronauts from January 15, 2005 solar flare
1.0	Maximum allowed dose for uranium miners inhaling rock dust each year
0.8	Dose during a14-day stay inside Space Shuttle during solar maximum and highest orbit elevation
0.3	Average cosmic ray and natural background dose each year
0.01	One flight across the North Pole from new York to Tokyo

The radiation dosages encountered by astronauts in space in properly shielded spacecraft rarely exceed the 'nuisance' level. There are no known examples of deaths directly attributable to excess radiation exposure among the over 300 astronauts that have worked in space for prolonged periods of time. Nevertheless, there are believed to be risks associated with even moderate radiation exposure. Radiation is measured in two ways:

Total absorbed dose (Rems)
Dosage rate (milliRems/hour)

A solar flare delivers a lot of radiation in a small amount of time, while cosmic rays deliver small amounts of radiation for a long period of time. Although the dosage rates are very different, their total absorbed dose can be similiar over a lifetime. The table to the left gives the various levels of radiation total dosage from a variety of sources.

Suppose that a round trip to Mars took one year through space, with an additional 0.5-year stay on the surface.

Problem 1 - What would be the total radiation exposure in rems if the trip occurred during sunspot minimum, and shielded astronauts encountered 2 flares like the one on January 15, 2005?

Problem 2 - How many times more radiation would these astronauts absorb in a year than if they had stayed on Earth?

Problem 1 - What would be the total radiation exposure in rems if the trip occurred during sunspot minimum, and encountered 2 flares like the one on January 15, 2005?
Answer: 40 rem from cosmic rays, 2x 1 rem for the flares, and 20x0.5 =10 rem on Mars gives **52 rem total** over 1.5 years.

Problem 2 - How many times more radiation would these astronauts absorb in a year than if they had stayed on Earth?
Answer: One year on Earth has a dosage of about 0.3 rems each year. The average Mars traveler in Problem 1 experienced 52 rem in 1.5 years or 35 rems/year, so this is about 35/0.3 = **115 times the Earth surface amoun**t.

Space radiation has not been a serious problem for NASA human missions because they have been short in duration or have occurred in low Earth orbit, within the protective magnetic field of the Earth," said Philip Scarpa, M.D., a NASA flight surgeon at NASA's Kennedy Space Center in Florida and co-investigator in the study. "However, if we plan to leave low Earth orbit to go back to the moon for long durations or on to Mars, we need to better investigate this issue and assess the risk to the astronauts in order to know whether we need to develop countermeasures such as medications or improved shielding. We currently know very little about the effects of space radiation, especially heavy element cosmic radiation, which is expected on future space missions and was the type of radiation used in this study.

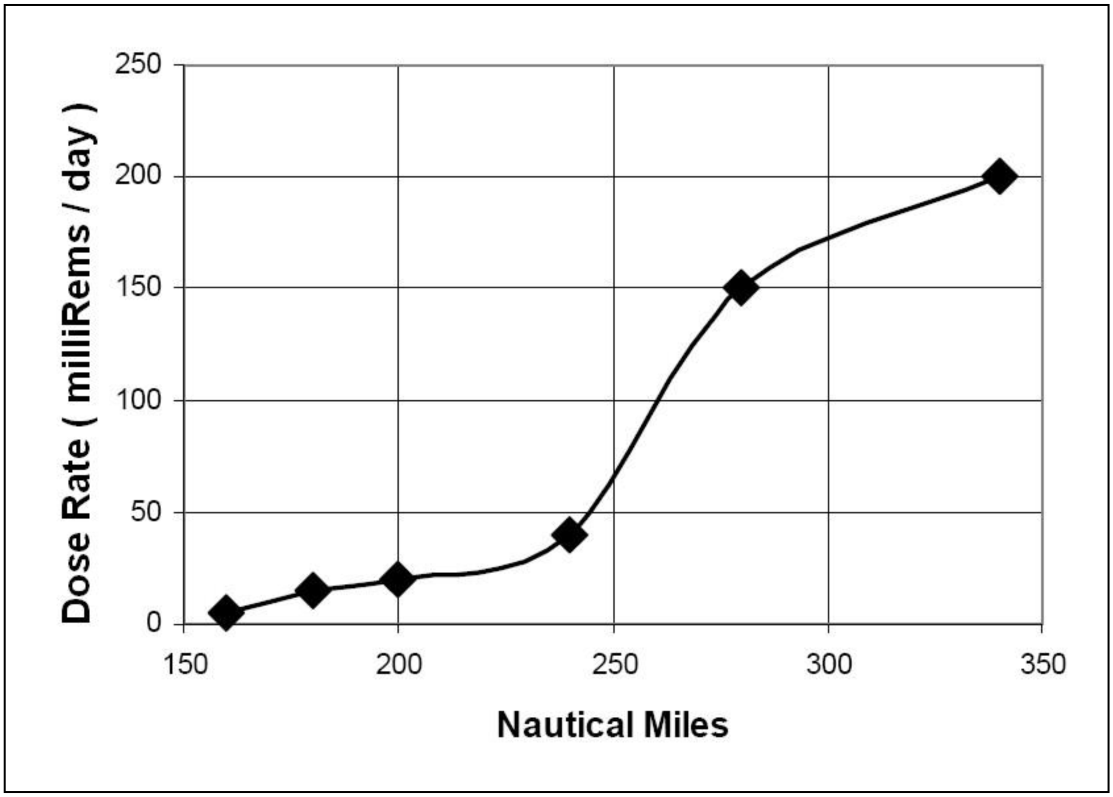
"In addition, we should expect that within each critical organ system, there may be different cell sensitivities that need to be considered when defining space radiation dose limits." Scarpa said.

The finding raises questions about the cognitive and emotional risks associated with radiation exposure during human space exploration missions.

"There is a growing body of evidence that the death of these types of cells is a potential adverse effect of radiation during cancer treatment, but it's not been discussed in terms of space travel," said Jack M. Parent, M.D., a neurologist at the University of Michigan who was not involved in the research. "Radiation has been associated with adverse cognitive effects, which is a potential hazard during space missions. Shielding and other measures to block the effects of radiation have to be strongly considered. The subject certainly deserves more study."

From http://www.news-medical.net/news/2007/12/12/33415.aspx?page=2

A Study of Astronaut Radiation Doses



The typical radiation dose rate on the ground is about 1.0 milliRem/day or 365 milliRem/year. This dose rate is considered safe, and it is an unavoidable part of the natural background that we live and work within. In space, however, this normal background dosage is significantly exceeded. The graph above shows the average radiation dose rate encountered by Space Shuttle astronauts during six Space Shuttle missions (from left to right: STS-42, 51, 51B, 37, 33 and 31).

Problem 1 - What was the daily radiation exposure experienced during the STS-31 mission?

Problem 2 - The International Space Station orbits Earth at an altitude of about 200 Nautical Miles. For a typical astronaut stay of 90 days, what will be the astronaut's average dose on the ISS?

Problem 3 - If the ISS astronaut remained on the ground during this 90-day mission, how much of a dose would he have acquired?

Answer Key

Problem 1 - What was the daily radiation exposure experienced during the STS-31 mission?

Answer: From the graph, the dose rate is **200 milliRems/day**.

Problem 2 - The International Space Station orbits Earth at an altitude of about 200 Nautical Miles. For a typical astronaut stay of 90 days, what will be the astronaut's average dose on the ISS?

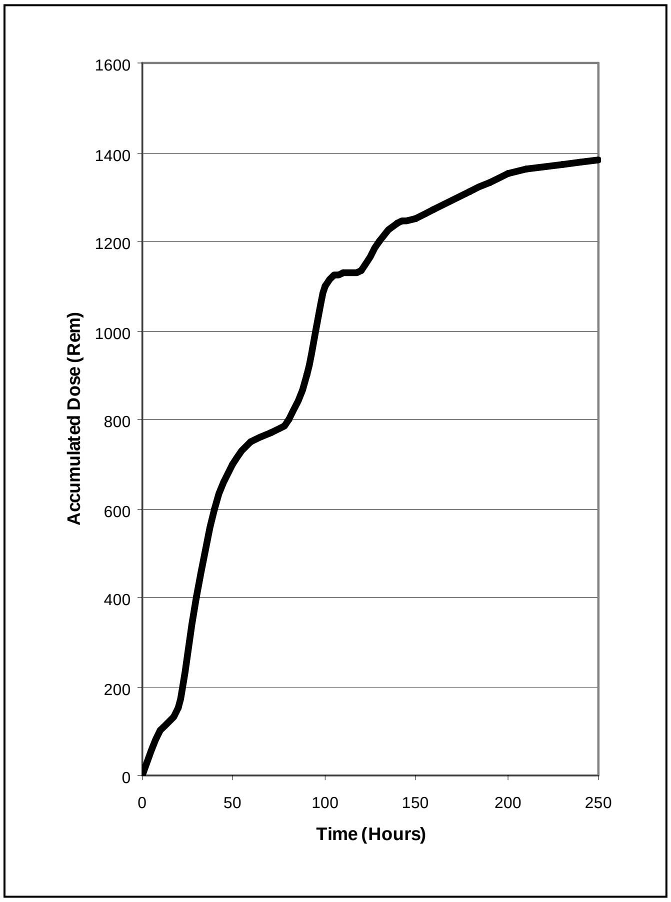
Answer: At an altitude of 200 NM, the daily dose rate is about 40 milliRems/day. During the 90-day mission, the astronaut absorbs about 40 milliRems/day x 90 days = **3,600 milliRems or 3.6 Rems of radiation**.

Problem 3 - If the ISS astronaut remained on the ground during this 90-day mission, how much of a dose would he have acquired?

Answer: The introductory paragraph says that on the ground the dose rate is 365 milliRad/year, so for 90 days the total radiation dose is
365 milliRems x (90/365) = **90 milliRems**.

Note: The radiation dose by the astronaut is the equivalent of 3600/365 = 9.8 years of ground-level exposure during a period of 90 days.

Dosage Curves for Solar Proton Events



The Solar Proton Event (SPE) of October, 1989 produced an intense series of radiation events that spanned about 250 hours in time before the particle stream ended. Every SPE is different, especially in the spectrum of particle energies that they produce. Some are classified as 'soft' because they have few particles with energies higher than about 50 million electron-volts (MeV). Others, such as the October event, have a considerable number of protons with energies far higher than 50 MeV and are called 'hard' SPEs.

Dr. Lawrence Townsend at the University of Tennessee used the energy spectrum and time history of this event to calculate the total, unshielded, accumulated radiation dosage shown in the graph to the left.

Problem 1 - What was the total radiation dose from the October 1989 Solar Proton Event after 250 hours (10.4 days)?

Problem 2 - A spacecraft is designed with aluminum walls that have a combined shielding of 19 gm/cm^2 to reduce incoming radiation by a factor of 500 times. What will be the accumulated radiation dose that the astronauts will be exposed to after:

A) 100 hours?

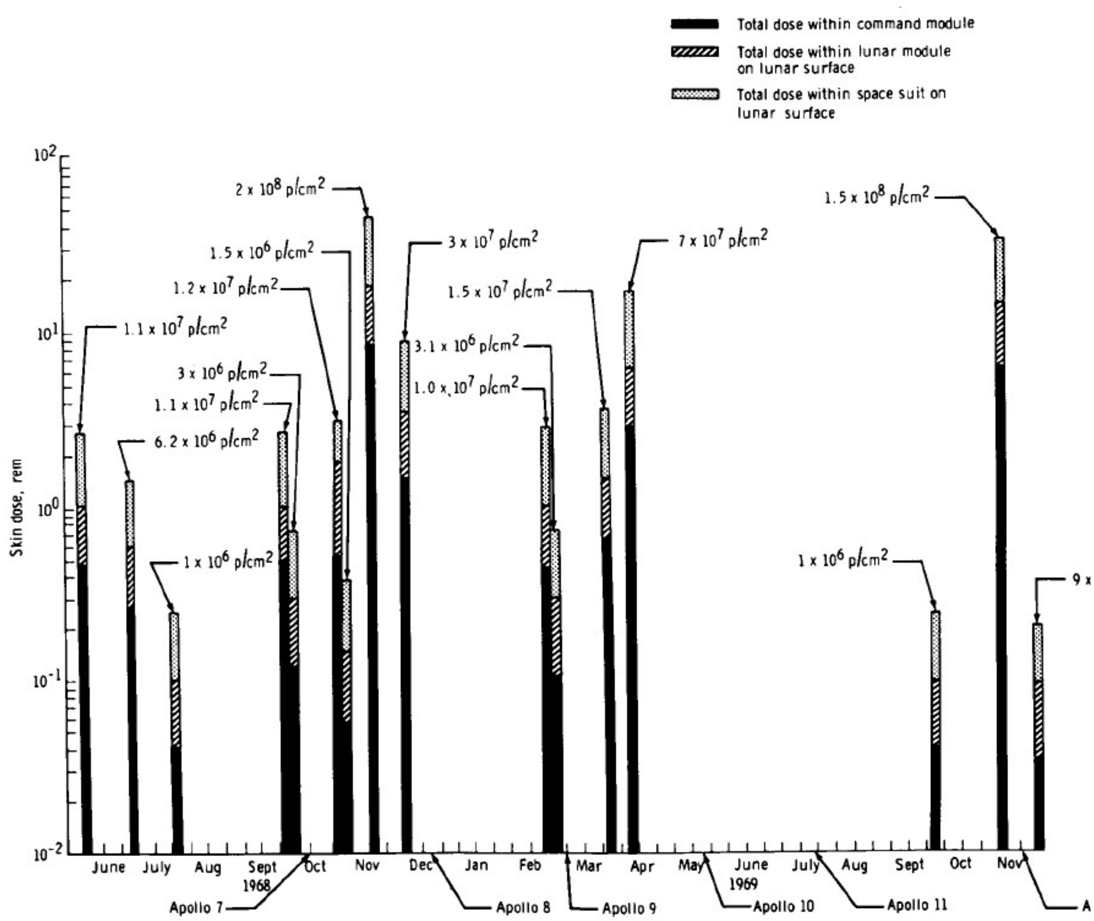
B) 200 hours?

Problem 1 - What was the total radiation dose from the October 1989 Solar Proton Event after 250 hours (10.4 days)? Answer: **About 1380 rems**.

Problem 2 - A spacecraft is designed with aluminum walls that have a combined shielding of 19 gm/cm^2 to reduce incoming radiation by a factor of 500 times. What will be the accumulated radiation dose that the astronauts will be exposed to after A) 100 hours? B) 200 hours?

Answer: A) At 100-hours, the outside dose is about 1120 rems. A 500x reduction yields a dose at that time of 1120/500 = **2.2 rems**. B) At 200 hours, the outside dose is about 1350 rems, so the inside astronaut dose is 1350/500 = **2.7 rems**.

Note: At ground-level on Earth, the background dose is 0.3 rems/year so a lifetime dose is about 20 rems. When properly shielded, astronauts are not exposed to hazardous levels of radiation even during intense solar flares…unless they happen to be outside the spacecraft in a spacesuit. Under those conditions, the radiation shielding is only 1 gm/cm^2, and radiation is only reduced by about 10%, making a Solar Proton Event like the one in October 1989 equal to 1380 rems x 0.8 = 1,104 rems which is lethal. This is why EVAs are the most risky undertaking by astronauts.



The logarithmic graph above shows the predicted skin doses for a series of solar proton events that occurred during the Apollo Mission Era between May 1968 and December 1969. The numbers in the graph also indicate the particle fluences in units of protons per square centimeter. Each bar is divided into portions that indicate the radiation levels expected: (black) inside the Command Module; (black+crosshatched) levels inside the Lunar Excursion Module (LEM), and (full height) levels expected inside a spacesuit on the lunar surface.

Problem 1 - Approximately what was the shortest, longest, and average time interval between SPEs during this period?

Problem 2 - For an astronaut in the well-shielded command module, what was the range in minimum to maximum skin doses?

Problem 3 - For an astronaut walking on the moon with a lightly-shielded spacesuit, what was the range in minimum to maximum doses during this period?

Problem 4 - During a 240-day voyage to Mars, inside a shielded compartment similar to the Command Module, what could be the average expected total dose if this range and frequency of SPEs were typical?

Problem 1 - Approximately what was the shortest, longest, and average time interval between SPEs during this period?

Answer: The graph provided by the NASA 'Apollo Experience Report - Protection Against Radiation (TN D-7080, March 1973) has a time axis that is a bit hard to interpret, but it seems that the tic-marks occur at intervals of about 10 days. There are 3 instances where the SPEs occur within a 10-day interval. The longest time interval is between the April, 1969 and September 1969 SPEs for an interval of about 5 **months**. The average time interval is 16 events / 19 months = 0.84 events/month or about 5 weeks. **Min = 10 days, average = 5 weeks, max = 5 months.**

Problem 2 - For an astronaut in the well-shielded command module, what was the range in minimum to maximum skin doses?

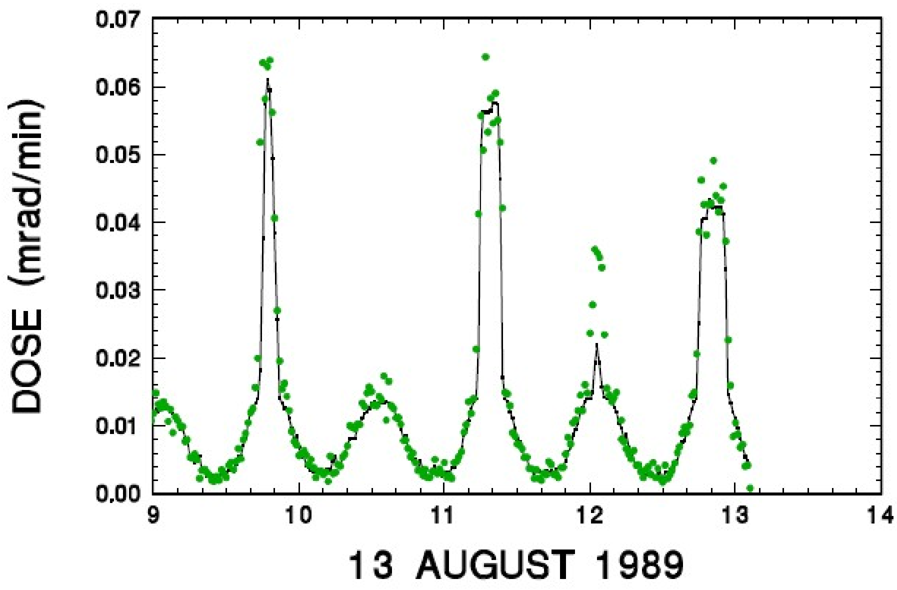
Answer: This dose data is indicated by the height of the black segment of each column. The minimum dose was about 0.03 Rem for the event during November 1969. The maximum dose was 8 Rem for November 1968. **[0.03 Rem, 8.0 Rem]**

Problem 3 - For an astronaut walking on the moon with a lightly-shielded spacesuit, what was the range in minimum to maximum doses during this period?

Answer: This would be the minimum and maximum height for the columns in the graph. The shortest column was for November 1969 with 0.2 rem, and the largest was for November 1969 with 35 rem. **[0.2 Rem, 35 Rem]**

Problem 4 - During a 240-day voyage to Mars, inside a shielded compartment similar to the Command Module, what could be the average expected total dose if this range and frequency of SPEs were typical?

Answer: We need to find the average total dose during the period from May 1968 to December 1969 (19 months) and then scale this to the 240-day (8-month) journey to Mars. Estimating from the height of the black bars in the figure, the total CM doses for the 16 events is (0.5 + 0.3 + 0.04 + 0.3 + 0.1 + 0.5 + 0.05 + 8.0 + 1.0 + 0.3 + 0.1 + 0.03 + 8.0 + 0.02) = 19.24 Rems in 19 months .Scaling to the Mars trip of 8 months we get 19.24 x 8/19 = **8.1 Rems**.



On August 13, 1989 the Space Shuttle mission STS-28 was in-flight at the time of a significant solar proton event (SPE). This SPE was one of the ten most intense events during the last 40 years.

The graph above shows the radiation dose rates to which the astronauts inside the Space Shuttle were exposed between 09:00 and 13:00 UT. The highest peaks correspond to locations in the Space Shuttle orbit where the incoming high-energy particles could reach the Space Shuttle.

Problem 1 - Looking at the graph above, what can you infer about the orbital period of the Space Shuttle during the time of the SPE?

Problem 2 - What was the maximum radiation dose rate during this storm period in units of A) milliRads/minute? B) milliSieverts/minute? (100 Rads = 1 Sievert)

Problem 3 - The average Space Shuttle radiation dose rate is about 0.015 milliRads/minute. Based upon the graph; A) predict how many orbits it will take for the peak SPE radiation levels to fall to the average Space Shuttle levels. B) What will be the cumulative radiation dose in Rads and Sieverts to which the astronauts will have been exposed during this time using the peak SPE radiation levels and the time duration over which they occur?

The figure is from a paper by Smart et al., 2001. 'Simulation of the solar proton dose observed during the STS-28 flight', Proceedings of the 27th International Cosmic Ray Conference. 07-15 August, 2001. Hamburg, Germany. Under the auspices of the International Union of Pure and Applied Physics (IUPAP)., p.4015

Problem 1 - Looking at the graph above, what can you infer about the orbital period of the Space Shuttle during the time of the SPE?

Answer: The average time between the radiation peaks is about 90 minutes, corresponding to the Space Shuttle orbit period.

Problem 2 - What was the maximum radiation dose rate during this storm period in units of A) milliRads/minute? B) milliSieverts/minute?

Answer: A) From the graph, the highest peak is the first one at about 09:50 UT. At D = 0.064 milliRad/minute.

B) 100 Rads = 1 Sievert, so 0.064 milliRads/minute = **6.4 milliSieverts/minute**.

Problem 3 - The average Space Shuttle radiation dose rate is about 0.015 milliRads/minute. Based upon the graph; A) predict how many orbits it will take for the peak SPE radiation levels to fall to the average Space Shuttle levels. B) What will be the cumulative radiation dose in Rads and Sieverts to which the astronauts will have been exposed during this time using the peak SPE radiation levels and the time duration over which they occur?

Answer: A) One possible progression is shown in the table below, which takes a total of 6 orbits:

Time	Dose rate (mrad/min)	Duration (minutes)	Dose (Rads)
09:50	0.064	15	0.96
11:20	0.058	15	0.87
12:50	0.048	15	0.72
14:20	0.038	15	0.57
15:50	0.028	15	0.42
17:20	0.018	15	0.27

B) The total dose is then the sum of the last column; **D = 3.8 Rads, or 0.038 Sieverts.**

Teacher Note: For Problem 3, students will need to extrapolate the data and may need some instruction on how to do this.

	Date	SPE (pFU)		Date	SPE (pFU)		Date	SPE (pFU)
1	11/4/1997	72	32	4/15/2001	951	63	7/22/2002	28
2	11/6/1997	490	33	4/18/2001	321	64	8/14/2002	26
3	4/20/1998	1,700	34	4/28/2001	57	65	8/22/2002	36
4	5/2/1998	150	35	5/7/2001	30	66	8/24/2002	317
5	5/6/1998	210	36	6/15/2001	26	67	9/7/2002	208
6	8/24/1998	670	37	8/10/2001	17	68	11/9/2002	404
7	9/25/1998	44	38	8/16/2001	493	69	5/28/2003	121
8	9/30/1998	1,200	39	9/15/2001	11	70	5/31/2003	27
9	11/8/1998	11	40	9/24/2001	12,900	71	6/18/2003	24
10	1/23/1999	14	41	10/1/2001	2,360	72	10/26/2003	466
11	4/24/1999	32	42	10/19/2001	11	73	10/28/2003	29,500
12	5/5/1999	14	43	10/22/2001	24	74	11/2/2003	1,570
13	6/2/1999	48	44	11/4/2001	31,700	75	11/4/2003	353
14	6/4/1999	64	45	11/19/2001	34	76	11/21/2003	13
15	2/18/2000	13	46	11/22/2001	18,900	77	12/2/2003	86
16	4/4/2000	55	47	12/26/2001	779	78	4/11/2004	35
17	6/7/2000	84	48	12/29/2001	76	79	7/25/2004	2,086
18	6/10/2000	46	49	12/30/2001	108	80	9/13/2004	273
19	7/14/2000	24,000	50	1/10/2002	91	81	11/1/2004	63
20	7/22/2000	17	51	1/15/2002	15	82	11/7/2004	495
21	7/28/2000	18	52	2/20/2002	13	83	1/16/2005	5,040
22	8/11/2000	17	53	3/17/2002	13	84	5/14/2005	3,140
23	9/12/2000	320	54	3/18/2002	53	85	6/16/2005	44
24	10/16/2000	15	55	3/20/2002	19	86	7/14/2005	134
25	10/26/2000	15	56	3/22/2002	16	87	7/27/2005	41
26	11/8/2000	14,800	57	4/17/2002	24	88	8/22/2005	330
27	11/24/2000	942	58	4/21/2002	2,520	89	9/8/2005	1,880
28	1/28/2001	49	59	5/22/2002	820	90	12/6/2006	1,980
29	3/29/2001	35	60	7/7/2002	22	91	12/13/2006	698
30	4/2/2001	1,110	61	7/16/2002	234			
31	4/10/2001	355	62	7/19/2002	31			

The high-energy particles in SPEs are a hazard to astronauts because this radiation can penetrate the shielding provided by spacesuits and spacecraft. Radiation dosage in given in terms of milliRems. Typically on the surface of Earth we are exposed to about 370 milliRem of natural radiation each year.

The table above gives the intensity of each SPE detected between 1996-2008. The intensity is given in particle flux units (pFUs) where 1 pFu = 1 particle/cm^2/sec. To convert pFUs into milliRems we use the following approximate conversion constants: Spacesuits: 10,000 pFU = 100 milliRem; Spacecraft: 10,000 pFU = 10 milliRem.

Problem 1 - What was the human radiation exposure in a spacesuit to the 5 most intense SPEs during the tabulated period?

Problem 2 - What was the human radiation exposure inside a spacecraft to the 5 most intense SPEs during the tabulated period?

To convert the pFUs into milliRems we use the following approximate conversion constants: Spacesuits: 10,000 pFU = 100 milliRem; Spacecraft: 10,000 pFU = 10 milliRem

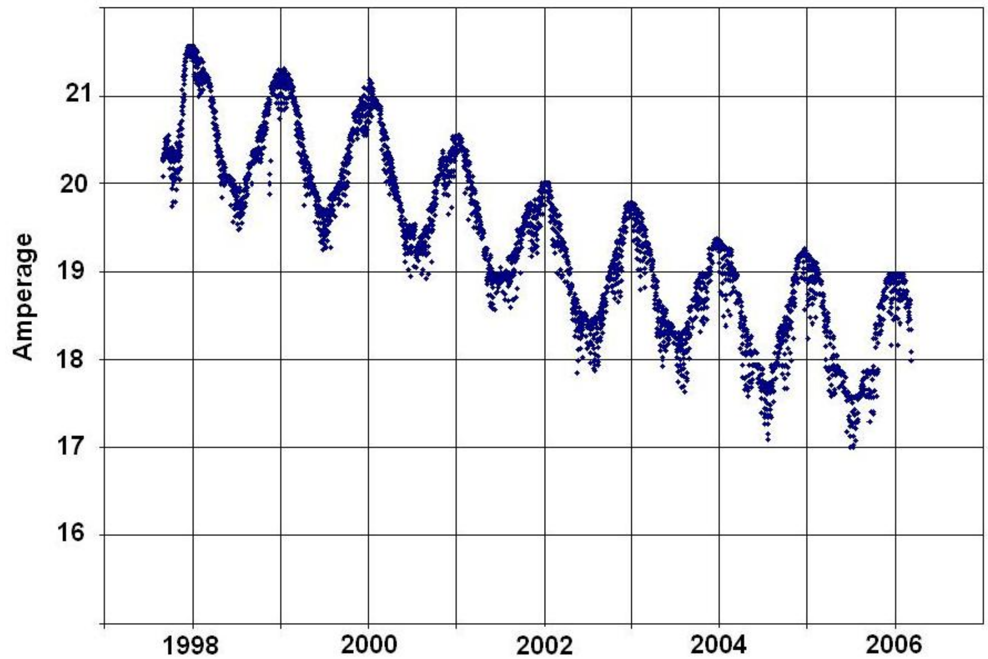
Problem 1 - What was the human radiation exposure in a spacesuit to the 5 most intense SPEs during the tabulated period?
Answer: The SPEs were 31,700 (11/4/2001); 29,500 (10/28/2003); 24,000 (7/14/2000); 18,900 (11/22/2001) and 14,800 (11/8/2000). The dosages were
31,700 pFU x 100 milliRem/10,000 = **317 milliRem**
29,500 pFU x 100 milliRem/10,000 = **295 milliRem**
24,000pFU x 100 milliRem/10,000 = **240 milliRem**
18,900 pFU x 100 milliRem/10,000 = **189 milliRem**
14,800 pFU x 100 milliRem/10,000 = **148 milliRem**

Problem 2 - What was the human radiation exposure inside a spacecraft to the 5 most intense SPEs during the tabulated period?
Answer:
31,700 pFU x 10 milliRem/10,000 = **32 milliRem**
29,500 pFU x 10 milliRem/10,000 = **30 milliRem**
24,000pFU x 10 milliRem/10,000 = **24 milliRem**
18,900 pFU x 10 milliRem/10,000 = **19 milliRem**
14,800 pFU x 10 milliRem/10,000 = **15 milliRem**

Note: At ground level, a one-year radiation dose is about 350 milliRem from natural sources, so a spacesuited astronaut exposed to a strong SPE receives about a years worth of radiation exposure in a matter of a few hours.

Note: pFU stands for 'particle flux unit' and is equal to a flux of 1 particle/cm^2/sec.

Power Loss in the ACE Satellite



The Advanced Composition Explorer (ACE) satellite is located at the 'L1' point in the Earth-Sun system, which is located 1.5 million kilometers from Earth along a line that connects the center of the sun with the center of Earth. From this vantage point, it has an unobstructed, stable view of the sun, and the conditions in interplanetary space far from Earth's messy environment.

From this location, outside Earth's protective magnetic field, it receives a steady rain of high-energy 'cosmic ray' particles that strike the satellite's solar panels and cause a steady loss of electrical power over time as the solar panels are eroded by the nuclear impacts.

The graph above shows decline in solar panel current between September 1998 and February 2006. The periodic 'ups and down' cycle is caused by the seasonal changes in the orientation of the solar panels relative to the sun, since the satellite orbits in the orbital plane of Earth.

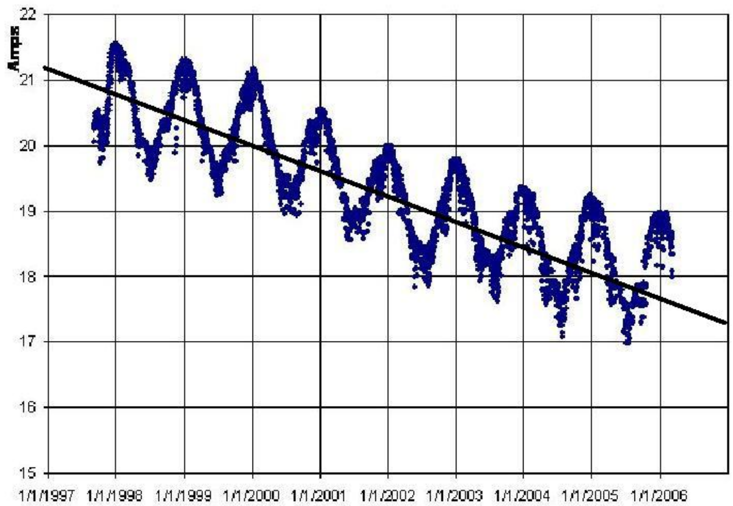
Problem 1 - Draw a line through the cycles that passes half-way between each of the maxima and minima of the curve.

Problem 2 - What is the slope of this line in Amperes/year?

Problem 3 - What is the percent change in the solar power in percent/year?

Problem 4 - What is the amperage of the solar panels by 1/1/2010?

Problem 1 - Draw a line through the cycles that passes half-way between each of the maxima and minima of the curve. Answer: **See below.**



Problem 2 - What is the slope of this line in Amperes/year?
Answer: Slope = (y2 - Y1) / (x2 - x1). Each horizontal division is 1 year so x2 - x1 = 10 years. The vertical change is from y1 = 21.1 to y2 = 17.3 or y2-y1 = -3.8 Amperes, so the slope is M = - 3.8/10 = **-0.38 amperes/year**.

Problem 3 - What is the percent change in the solar power in percent/year?

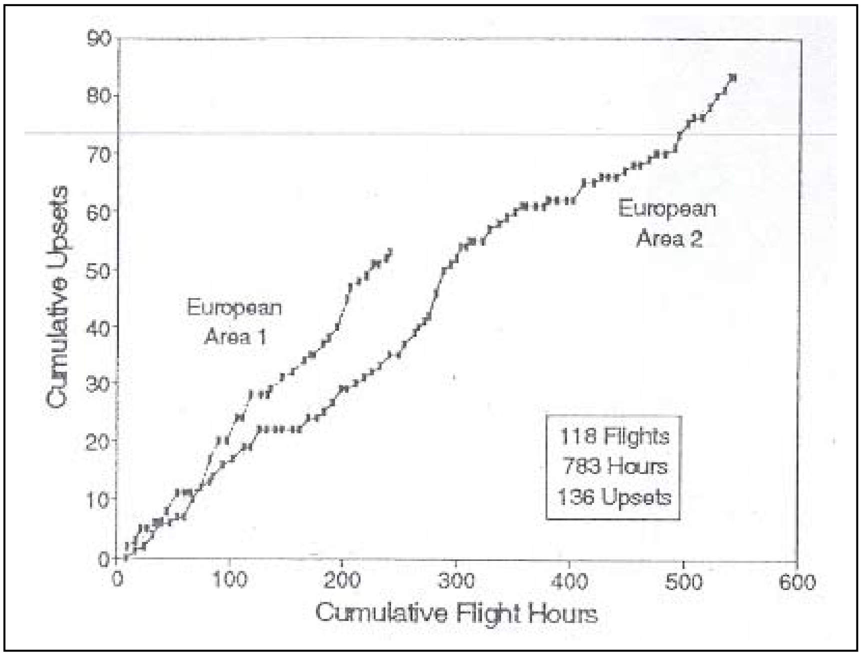
Answer: Selecting the average value of the amperage over this time interval we have A = (17.3 + 21.1)/2 = 19.2 Amperes. Then the percent change is just
P = 100% x (-0.38/19.2) or **P = -2.0% / year**.

Problem 4 - What is the amperage of the solar panels by 1/1/2010?

Answer: The date 1/1/2010 is 13 years from the start of the data in the graph for which A = 21 amperes, so after 13 years it will be A = 21.0 - 0.38 (13) or **A = 16.1 amperes.**

In 2001, the NASA Altair, Unmanned Air Vehicle (UAV) flew its first flight at an altitude of 100,000 feet. Designed by NASA-Dryden engineers and scientists, it is designed to fly for up to 48 hours to complete a variety of science research studies of Earth.

Because of the complexity of the computer systems (called avionics) onboard, special attention had to be paid to cosmic ray showers. These particles, mostly neutrons, pass through the walls of the aircraft and can affect computer memory. At 30,000 feet, the neutron flux is 0.3 neutrons/cm^2/sec but at 100,000 feet the neutron flux is 1.2 neutrons/cm^2/sec.



The above plot gives the cumulative number of memory upsets (called Single Event Upsets or SEUs) at an altitude of 30,000 feet after a given number of cumulative hours in the air. The total memory size was 1 billion bits (125 megabytes). A SEU consists of one bit in a data word being changed from a '0' to a '1' or vice versa. For example, in the airspace of European Area 2 there would be 20 SEUs (bit changes) out of 1 billion bits after 150 hours in total flight time.

Problem 1 - If each upset involved one bit having the wrong data value due to a single neutron impact, about how many SEUs were registered after 5 flights totaling 300-hours at 100,000 feet and for the same-sized memory (125 megabytes)?

Problem 2 - How long do you have to wait for an SEU to occur at A) 30,000 feet? B) 100,000 feet?

Problem 3 - If the total area of the memory module is 10 cm^2, during the UAV 300-hour flight, how many neutrons pass through the memory module?

Problem 4 - What are the odds that a single memory bit will be corrupted by a neutron impact in 300-hours?

Problem 1 - If each upset involved one bit having the wrong data value due to a single neutron impact, about how many bit upsets were registered after 5 flights totaling 300-hours at 100,000 feet, and for the same-sized memory (125 megabytes)?

Answer: The graph indicates that at 30,000 feet the 300-hour upset rate is about 50 events. Because the discussion states that 1 upset is caused by 1 neutron, the upset rate is proportional to the neutron flux. At 30,000 feet, the neutron flux is 0.3 neutrons/cm^2/sec but at 100,000 feet the neutron flux is 1.2 neutrons/cm^2/sec, so there should be 4-times the number of upsets at 100,000 feet per unit time and area. So, at 100,000 feet, during a 300-hour total flight time, we should see about 4 x 50 = **200 memory upset** events for the same-sized memory.

Problem 2 - How long do you have to wait for an upset to occur at A) 30,000 feet? B) 100,000 feet?

Answer: A) 300 hours / 50 upsets = 6 hours.
B) 300 hours / 200 upsets = 1.5 hours.

Problem 3 - If the total area of the memory module is 10 cm^2, during the UAV 300-hour flight, how many neutrons pass through the memory module?

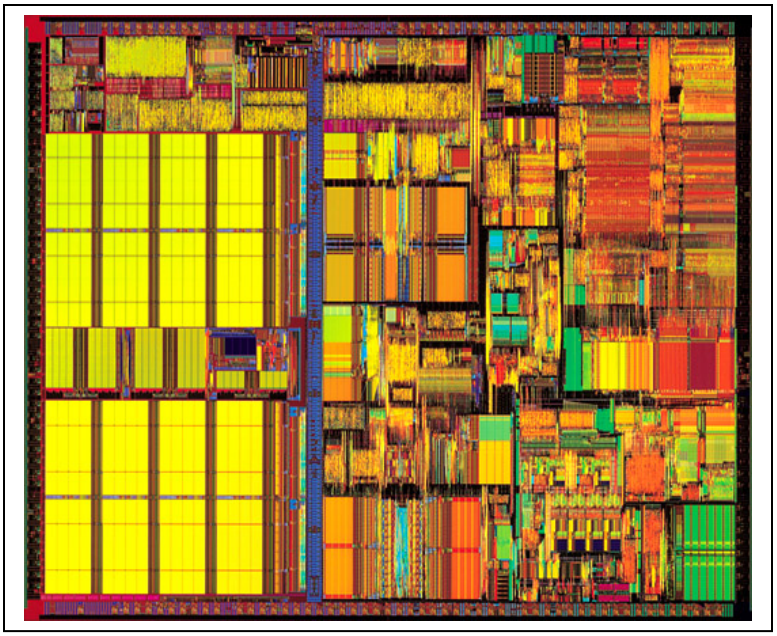
Answer: The neutron flux is 1.2 neutrons/cm^2/sec, so for A =10 cm^2 and T = 300 hrs x 3600 sec/hr = 1,080,000 seconds, we have N = FAT = 120 neutrons/sec x 1,080,000 seconds = **129,600,000 neutron**s.

Problem 4 - What are the odds that a single memory bit will be corrupted by a neutron impact in 300-hours?

Answer: There were 200 upsets at 100,000 feet in 300 hours, so the odds that one neutron will cause one upset is 200 / 129600000 = **1 in 648,000.**

Note: If we use the total memory size of 1 billion bits the odds would be 1 in 8 that a memory cell would be impacted by a neutron, but not all impacts actually cause an upset.

The figure was based on data taken from aircraft flying at 29,000 feet, from a research paper by Taber and Normand (1993), and published in the IEEE Transactions on Nuclear Science, vol. 40, No. 2, pp 120.



Computers are used in space, but that means they can get clobbered by radiation and develop 'glitches' in the way they work. Sometimes these glitches cause the satellite to fail, or transmit corrupted data.

This is a photo of the Pentium III microprocessor board is about 15 cm wide. The solid, colored rectangular areas are memory locations that store data, the computer operating system, and other critical information.

Suppose that 2/3 of the area of a satellite's processor memory is used for data storage, 1/4 is for the computer's operating system, and the remainder is for program storage.

Problem 1 - Suppose that the total size of the memory is 1,200 megabytes. How many megabytes are available for program storage?

Problem 2 - Suppose that for a satellite in space, cosmic rays cause glitches and errors in the computer memory at a rate of 1 glitch per hour for every 1 gigabytes of memory. If the satellite is in operation for 10 hours, how many glitches will this satellite's memory encounter?

Problem 3 - Given the areas of the different computer memory functions, how many glitches would you expect in the operating system memory?

Problem 4 - After 10 hours of operation, about how many operating system failures would you expect, and what would be the average time between operating system failures?

Problem 5 - An engineer decides to re-design the satellite's memory by splitting up the memory for the operating system into 4 separate areas. Why do you think this design might reduce the number of glitches caused by the cosmic rays, or why would this not work?

Answer Key

Problem 1 - Suppose that the total size of the memory is 1,200 megabytes. How many megabytes are available for program storage? Answer: Program storage is 1 - 2/3 - 1/4 = 12/12 - 8/12 - 3/12 = 1/12 of the memory. Since there are 1,200 megabytes of computer memory for all functions, the program memory occupies 1,200 megabytes x 1/12 = **100 megabytes**.

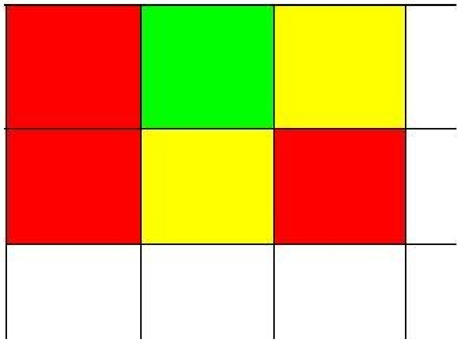
Problem 2 - Suppose that for a satellite in space, cosmic rays cause glitches and errors in the computer memory at a rate of 1 glitch per hour for every 1 gigabytes of memory. If the satellite is in operation for 10 hours, how many glitches will this satellite's memory encounter? Answer: The computer memory is 1,200 megabytes and since 1,000 megabytes = 1 gigabyte, the memory is 1.2 gigabytes in size. 1 glitch/hour per gigabyte x 1.2 gigabytes = 1.2 glitches/hour. For 10 hours the total number of glitches will be 1.2 x 10 = **12 glitches for the entire memory area.**

Problem 3 - Given the areas of the different computer memory functions, how many glitches would you expect in the operating system memory? Answer: The operating system occupies 1/4 of the memory, so if the glitches are random, the operating system should experience 12 glitches x 1/4 = **3 glitches.**

Problem 4 - After 10 hours of operation, about how many operating system failures would you expect, and what would be the average time between operating system failures? Answer: In 10 hours, the average time between operating system glitches would be 10 hours / 3 glitches = **3 1/3 hours between glitches.**

Problem 5 - An engineer decides to re-design the satellite's memory by splitting up the memory for the operating system into 4 separate areas. Why do you think this design might reduce the number of glitches caused by the cosmic rays, or why would this not work? Answer: **No, because the total area of the operating system memory is exactly the same, so the probability that it will receive a glitch remains the same as before.**

Correcting Bad Data Using Parity Bits



The first few pixels in a large image

Data is sent as a string of '1's and '0's which are then converted into useful 'base-10' numbers by computer programs.

In the sample image to the left, red is represented by the data word '10110011', green is represented by '11100101' and yellow by the word '00111000', so the first three pixels (red,green,yellow) would be transmitted as the 'three word' string '101100111110010100111000'.

But what if one of those 1-s or 0-s were accidentally reversed? In space, cosmic ray particles can 'corrupt' data in just this way.

Since the beginning of the Computer Era, engineers have anticipated this problem by adding a 'parity bit' to each data word. The bit is '1' if there are an even number of 1's in the word, and' 0' if there is an odd number. In the data word for red '1011001**1**' the last '**1**' to the right is the parity bit. For example, Data Word A '1110001**1**' is valid but Data Word B '1111001**1**' is not. There are five '1's in Data Word B, but instead of the parity bit being '0' ('1110001**0**'), it is '1' which means Data Word B had one extra '1' added somewhere. One way to recover the good data is to simply re-transmit data words several times and fill-in the bad data words with the good words from one of the other transmissions. For example:

	Word 1	Word 2	Word 3	Word 4	Word 5
Corrupted data string:	1011110**0**	101101**0**	1010101**1**	0011001**1**	1011101**0**
Good data string:	1011110**0**	100101**0**	1010101**1**	1011001**1**	1011101**0**

The second and fourth words have been corrupted, but because the string was re-transmitted twice, we were able to 'flag' the bad word and replace it with a good word with the correct parity bit.

Problem: Below are two data strings that have been corrupted by cosmic ray glitches. Look through the data (a process called parsing) and use the right-most parity bit to identify all the bad data. Create a valid data string that has been 'de-glitched'.

String 1:	10111010	11110101	10111100	11001011	00101101
	01010000	01111010	10001100	00110111	00100110
	01111000	11001101	10110111	11011010	11100001
	10001010	10001111	01110011	10010011	11001011

String 2:	10111010	01110101	10111100	11011011	10101101
	01011010	01111010	10001000	10110111	00100110
	01101000	11001101	10110101	11011010	11110001
	10001010	10011111	01110011	10010001	11001011

Answer key

Problem: Below are two data strings that have been corrupted by cosmic ray glitches. Look through the data (a process called parsing) and use the right-most parity bit to identify all the bad data. Create a valid data string that has been 'de-glitched'.

The highlighted data words are the corrupted ones.

String 1:	10111010	**11110101**	10111100	11001011	**00101101**
	01010000	01111010	10001100	00110111	00100110
	01111000	11001101	**10110111**	11011010	**11100001**
	10001010	10001111	01110011	**10010011**	11001011

String 2:	10111010	01110101	10111100	**11011011**	10101101
	01011010	01111010	**10001000**	**10110111**	**10100110**
	01101000	11001101	10110101	11011010	11110001
	10001010	**10011111**	01110011	10010001	**01001011**

In the first string, 11110101 has a parity bit of '1' but it has an odd number of '1s' so its parity should have been '0' if it were a valid word. Looking at the second string, we see that the word that appears at this location in the grid is '01110101' which has the correct parity bit. We can see that a glitch has changed the first '1' in String 2 to a '0' in the incorrect String 1.

By replacing the highlighted, corrupted data words with the uncorrupted values in the other string, we get the following de-glitched data words:

Corrected:	10111010	01110101	10111100	11001011	10101101
	01011010	01111010	10001100	00110111	00100110
	01101000	11001101	10110101	11011010	11110001
	10001010	10001111	01110011	10010001	11001011

Cosmic Rays and Satellite Anomalies

Year	SSN	GCR	**R**	Year	SSN	GCR	**R**
1979	155	80	0.1	1992	94	64	0.0
1980	154	76	0	1993	54	96	0.3
1981	140	56	0.7	1994	29	104	0.9
1982	116	72	0.5	1995	17	112	0.8
1983	66	40	0.8	1996	8	116	0.6
1984	45	80	1.8	1997	21	116	0.3
1985	17	88	2.4	1998	64	120	0.2
1986	13	104	2.3	1999	93	104	0.2
1987	29	112	1.2	2000	119	72	0.3
1988	100	96	1.0	2001	110	64	0.3
1989	157	56	0.7	2002	104	72	0.2
1990	142	24	0.5	2003	63	64	0.1
1991	145	40	0.1				

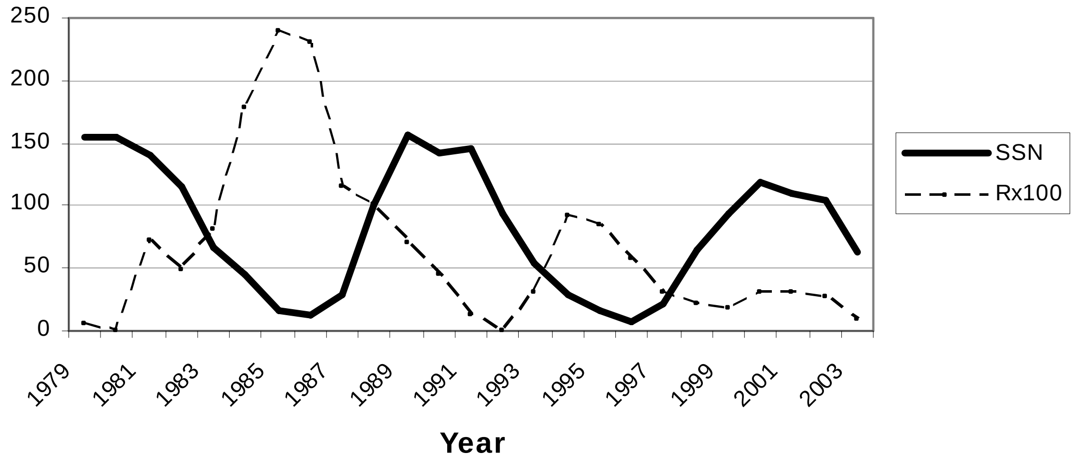
Satellite anomalies are conditions in which a satellite suddenly operates in a way not consistent with its commanded state, or where data has been temporarily corrupted. This can result in operator intervention to correct the problem. It can also cause serious damage to a satellite if the anomaly is too severe.

The table shown above is a summary of the anomaly logs from a study published by Drs David Wilkinson and Joseph Allen in 1997. Their survey included 5,033 satellite anomalies that occurred between 1970 and 1997 and were reported by the operators of 259 satellites. The table summarizes the anomalies reported for 33 of these satellites that were located in geosynchronous orbit during the indicated years. The columns give the average sunspot number for each year (SSN) and the intensity of the cosmic rays detected by satellite instruments (GCR). The column indicated by 'R' is the rate of satellite anomalies for that year in units of anomalies per satellite per year. For example, in 1985 a single satellite would experience about 2.4 anomalies during that year.

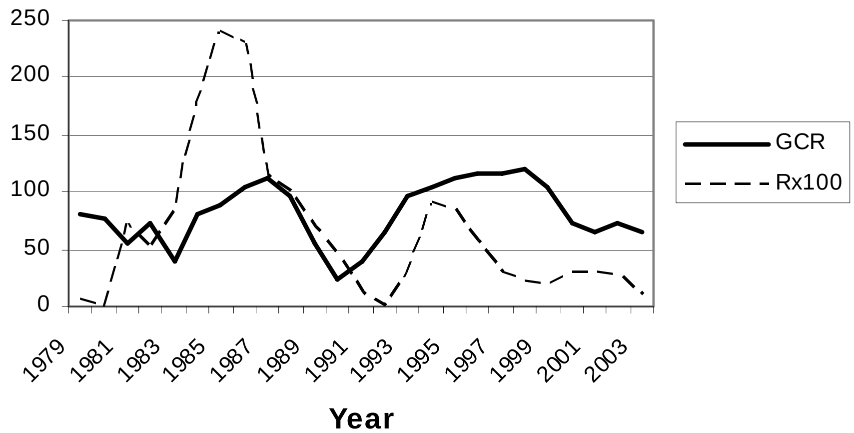
Problem 1 - Graph the quantity R and A) the Cosmic Ray rate, GCR, defined in the table, and B) The sunspot number for each year. (Hint: For convenience, plot 100xR on the same scale as sunspot number).

Problem 2 - From your graphs in Problem 3, does the average number of satellite anomalies each year correlate more closely with the number of sunspots or the cosmic ray rate?

Problem 1 - Graph the quantity R and A) the Cosmic Ray rate, GCR, defined in the table, and B) The sunspot number for each year.
Answer: A) Anomalies with sunspot counts:



B) Anomalies with Cosmic Ray Intensity:



Problem 2 - From your graphs in Problem 3, does the average number of satellite anomalies each year correlate more closely with the number of sunspots or the cosmic ray rate?

Answer: **The correlation appears to be the strongest with cosmic ray intensity because the peaks and valleys line up in time a bit better.**

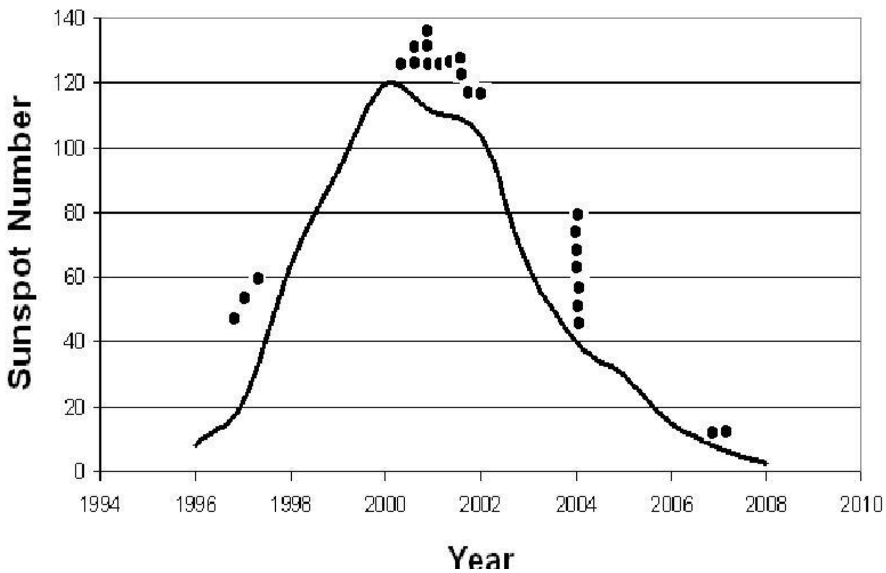
Event Date	AP*	SSN	SPE	Flare	Satellite	Condition
1-11-1997	------	7	---------	--------	Telstar-401	Satellite failure - Pointing/attitude
4-11-1997	------	23	72	--------	Tempo-2	Transponder loss
9-20-1997	46	14	---------	M1.7	Adeos-1	Main computer malfunction - GCR
3-21-2000	------	150	---------	M1.8	Hotbird-2	Loss of service for 9 hours
4-9-2000	137	108	55	M3.1	Brazilsat-A2	Loses TWTA
4-28-2000	------	124	--------	M7.8	Turksat-1C	ESD causes 55-minute service loss
7-15-2000	192	148	24,000	X5.7	GOES-8	Electron sensor problems- power
7-15-2000	192	148	24,000	X5.7	GOES-10	Data corruption
7-15-2000	192	148	24,000	M1.3	ASCA	Satellite Failure and reentry
8-27-2000	45	113	--------	--------	Solidaridad-1	Backup SCP fails
10-31-2000	41	111	---------	M4.4	Echostar-4	26/44 transponders lost
11-4-2000	78	130	---------	-------	Insat-2B	Service outage
9-6-2001	------	141	---------	M2.2	PAS-7	25% power loss
10-23-2001	105	143	24	X1.2	Echostar-6	Solar array string loss announced
12-7-2001	------	138	---------	M1.0	Arabsat-3A	Loss of transponders
10-25-2003	42	88	---------	--------	Adeos-2	Satellite Failure - Solar array malfunction
10-28-2003	252	165	29,500	X17.2	DRTS	Enters Safe Mode
10-28-2003	252	165	29,500	X17.2	FEDSAT	Magnetometer data corrupted
10-28-2003	252	165	29,500	X17.2	GOES-8	X-ray sensor disabled
10-30-2003	252	167	29,500	X10.0	INMARSAT	CPU outages and attitude errors
10-30-2003	252	167	29,500	X10.0	KODAMA	Goes into Safe Mode
10-30-2003	252	167	29,500	X10.0	DMSP F14	One microwave sounder damaged
9-23-2006	-----	8	---------	--------	Meteosat-8	SEU
12-5-2006	120	20	1,980	X9.0	GOES-13	X-ray imager damaged

The table gives a short list of the publicly-admitted satellite failures and outages during sunspot cycle 23 (1996-2008).

Problem 1 - The annual sunspot counts for Cycle 23 between 1996 and 2008 (inclusive) were as follows: [9,21,64,93,120,111,104,64,40,30,15,8,3]. How do the outages compare in time with the sunspot cycle? (Hint: Graph the sunspot cycle and then indicate on the graph when the outages occurred)

Problem 2 - Assuming that this list is complete, what is the probability that a satellite outage/failure will occur during a solar proton event?

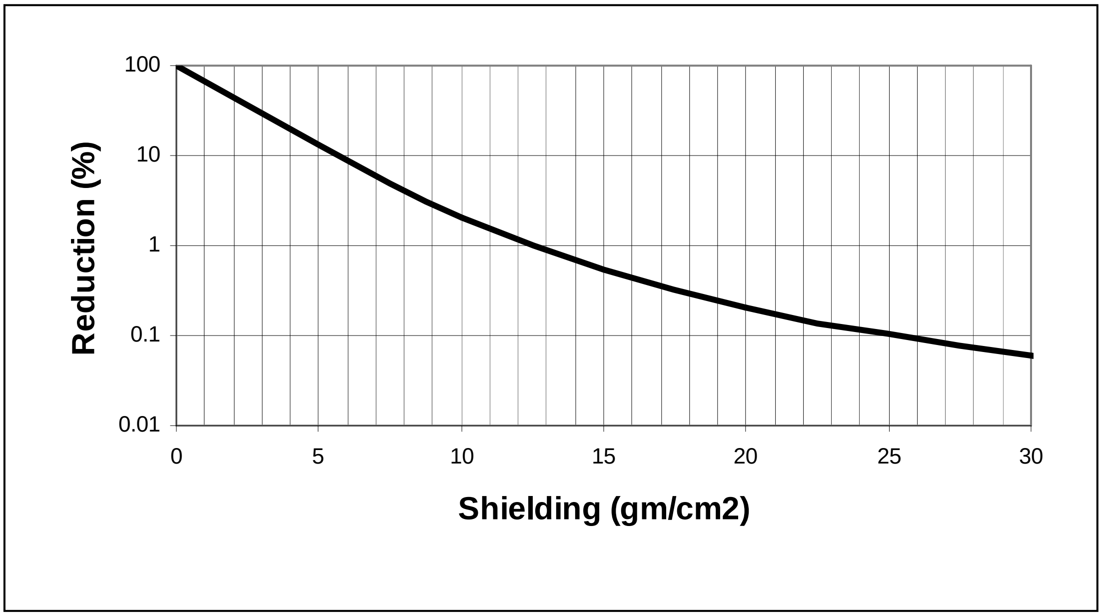
Problem 1 - The annual sunspot counts for Cycle 23 between 1996 and 2008 (inclusive) were as follows: [9,21,64,93,120,111,104,64,40,30,15,8,3]. How do the outages compare in time with the sunspot cycle? (Hint: Graph the sunspot cycle and then indicate on the graph when the outages occurred) Answer: **The graph below shows the sunspot cycle (line) and dots representing the approximate dates of the outages. The outages can come at any time in the cycle, but are most common close to the peak of the cycle.**



Problem 2 - Assuming that this list is complete, what is the probability that a satellite outage/failure will occur during a solar proton event?

Answer: The total number of satellite outages is 24, of which 13 were reported during SPE events so the probability is 100% x 13/24 = **54%**.

How to Calculate Shielding Thickness



Most people have heard that radiation can be blocked or 'shielded' so that it does less harm to humans. Often, substances such as lead are used when weight is not an issue. But for space applications, weight costs money, approximately $8,000 per pound for Earth-orbiting payloads.

Radiation in space can be electromagnetic (x-rays and gamma rays) or particulate (protons, electrons, alpha-particles), and each has to be blocked to safe levels so that satellites and astronauts are not harmed.

There are many different materials that can be used as radiation shielding. We will focus on aluminum, which is a common ingredient to spacecraft and satellite walls. The curve above gives the percentage of reduction in the radiation as a function of the shielding coefficient in grams/cm^2. Spacesuits typically have 1 gm/cm^2 of shielding while the walls (bulkhead) of the Space Shuttle can be 10 gm/cm^2.

Problem 1 - A plate of aluminum is 4.8 centimeters thick. If the density of aluminum is 2.7 gm/cm^3, what will be A) the shielding coefficient? B) The reduction factor of the radiation passing through the shield?

Problem 2 - A rare Carrington Superflare produces about 6,000 rem on the outside wall of a spacecraft. What must be the shielding thickness so that no more than 6 rem makes it through to the astronauts?

Problem 3 - The astronauts in a spacecraft will be in space for 2 years, in a radiation environment that could produce as much as 500 rems/year of radiation. What is the minimum spacecraft wall thickness that will allow the astronauts to accumulate no more than 1 rem of radiation during the entire voyage?

Problem 1 - A plate of aluminum is 4.8 centimeters thick. If the density of aluminum is 2.7 gm/cm^3, what will be A) the shielding coefficient? B) The reduction factor of the radiation passing through the shield?

Answer: A) 2.7 gm/cm^3 x 4.8 cm = **13 gm/cm^2**. B) From the graph, at a shielding of 13 gm/cm^2, the curve indicates '1%' so the radiation has been reduced in strength by a factor of **100 times**.

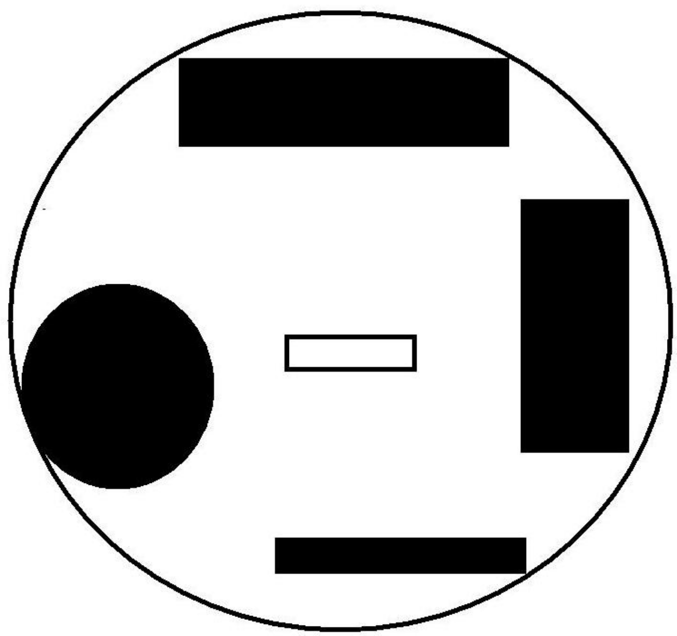
Problem 2 - A rare Carrington Superflare produces about 6,000 rem on the outside wall of a spacecraft. What must be the shielding thickness so that no more than 6 rem makes it through to the astronauts?

Answer: We need to reduce the radiation to 100% x (6/6000) = 0.10%. From the curve, this will occur for shielding greater than about **25 gm/cm^2**.

Problem 3 - The astronauts in a spacecraft will be in space for 2 years, in a radiation environment that could produce as much as 500 rems/year of radiation. What is the minimum spacecraft wall thickness that will allow the astronauts to accumulate no more than 1 rem of radiation during the entire voyage?

Answer: The total radiation dosage for the trip is 2 years x (500 rem/year) = 1000 rems. We want this to be no more than 1 rem inside the spacecraft so the incoming radiation it must be reduced by a factor of 1/1000 or 0.1%. From the vertical scale on the graph we see that '0.1' corresponds to a shielding of 24 gm/cm^2 of aluminum. Because the density of aluminum is 2.7 gm/cm^3, the wall thickness would be 24/2.7 = **8.9 centimeters**. This is the minimum thickness, and thicker walls will reduce the radiation levels even further.

With passive shielding, the placement of objects near a radiation-sensitive device provides some shielding against incoming particles. Imagine that a spherical satellite has a cross-section as shown below. The volume contains various tanks and instrument packages (blackened shapes) that partially fill the interior and are opaque to cosmic radiation. A very sensitive microprocessor is located at the center of the satellite, and is represented by the white box in the figure below. Only for a limited number of directions will external radiation be able to reach the microprocessor.

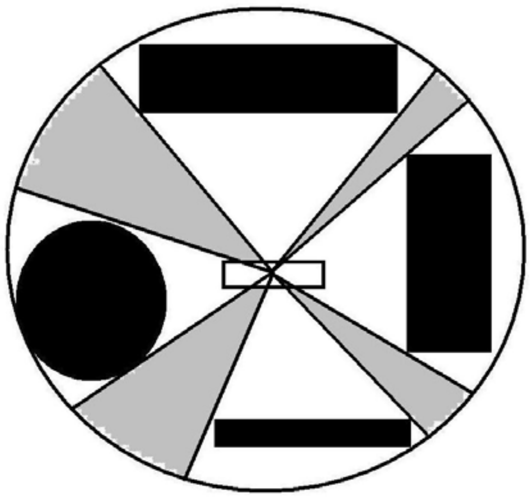


Problem 1 - By drawing triangles with vertex at the center of the white box, and base on the circumference of the outer circle, indicate all of the ways in which cosmic rays can reach the microprocessor box.

Problem 2 - About what fraction of the satellite's perimeter represent entry ways for cosmic rays into the microprocessor box?

Problem 3 - If the microprocessor has an area of 20 cm^2, and the flux of the cosmic rays is 1000 protons/cm^2/sec, how many cosmic ray protons will strike the microprocessor each second?

Problem 1 - By drawing triangles with vertex at the center of the white box, and base on the circumference of the outer circle, indicate all of the ways in which cosmic rays can reach the microprocessor box. Answer: See below gray-shaded areas

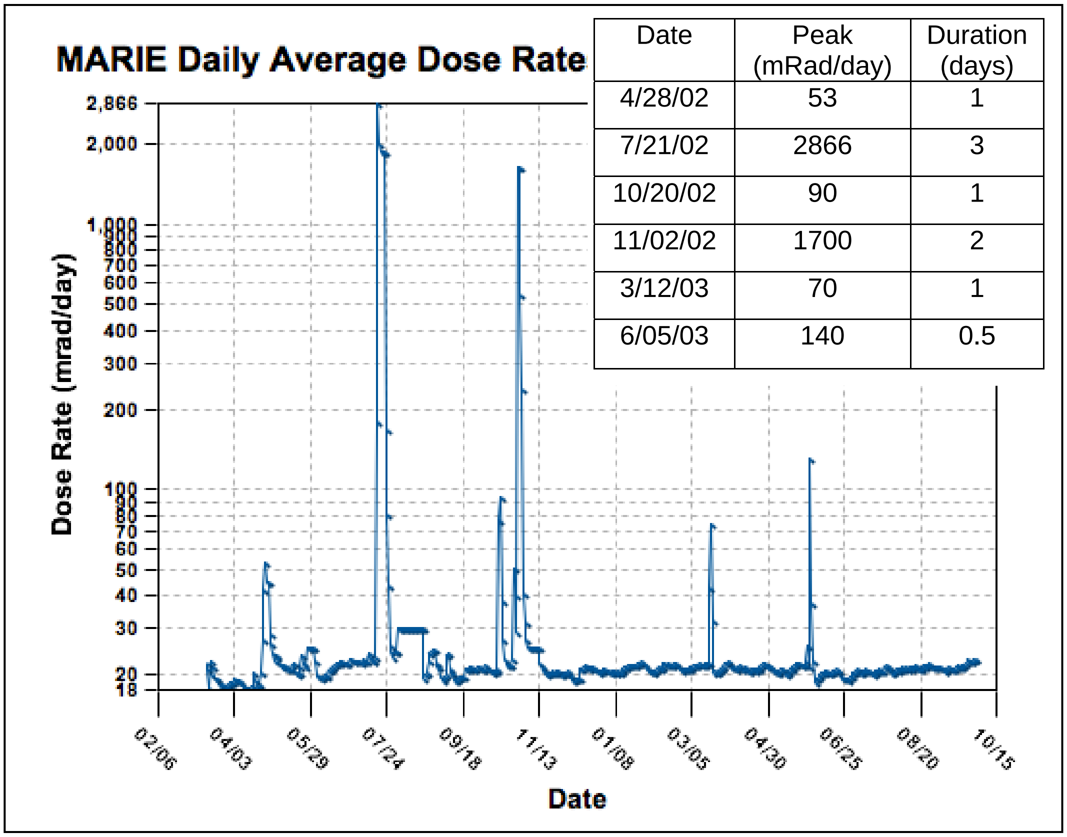


Problem 2 - About what fraction of the satellite's perimeter represent entry ways for cosmic rays into the microprocessor box?

Answer: The total length of the arcs are approximately 70 degrees, so the fraction is 70/360 = **1/5**. So the shielding provided by the various boxes inside the satellite block about 4/5 of the incoming radiation from reaching the microprocessor.

Problem 3 - If the microprocessor has an area of 20 cm^2, and the flux of the cosmic rays is 1000 protons/cm^2/sec, how many cosmic ray protons will strike the microprocessor each second?

Answer: 1000 protons/cm^2/sec x 20 cm^2 x 1/5 = **4000 protons/sec**.



Date	Peak (mRad/day)	Duration (days)
4/28/02	53	1
7/21/02	2866	3
10/20/02	90	1
11/02/02	1700	2
3/12/03	70	1
6/05/03	140	0.5

The NASA, Mars Radiation Environment Experiment (MARIE) measured the daily radiation dosages from a satellite orbiting Mars during the 500-day period beginning on March 13, 2002. The dose rate shown in the figure above is given in units of milliRads/day.

The six tall 'spikes' are Solar Proton Events (SPEs), which are related to solar flares. The rest of the plotted data (the wiggly line!) is the dose rate caused by galactic cosmic rays (GCRs). The table above gives the information for the six SPEs.

Problem 1 - The graph shows that the average cosmic ray dose rate was about 20 milliRads/day. What is the total cosmic ray radiation exposure in Rads during this time period?

Problem 2 - The product of dose rate times duration gives the total radiation exposure. From the tabulated data, A) What is the total radiation exposure in Rads of the combination of all six SPEs during this time interval? B) What is the total dose in Rems if 1 Rad = 2 Rems for cosmic rays?

Problem 3 - Which radiation source, SPEs or cosmic rays, has the largest percentage contribution to an astronaut's total radiation exposure?

Problem 1 - The graph shows that the average cosmic ray dose rate was about 20 milliRads/day. What is the total cosmic ray radiation exposure in Rads during this time period?

Answer: 20 milliRads/day x 500 days = **10 Rads**.

Problem 2 - The product of dose rate times duration gives the total radiation exposure. From the tabulated data, what is the total radiation exposure in Rads of the combination of all six SPEs during this time interval?

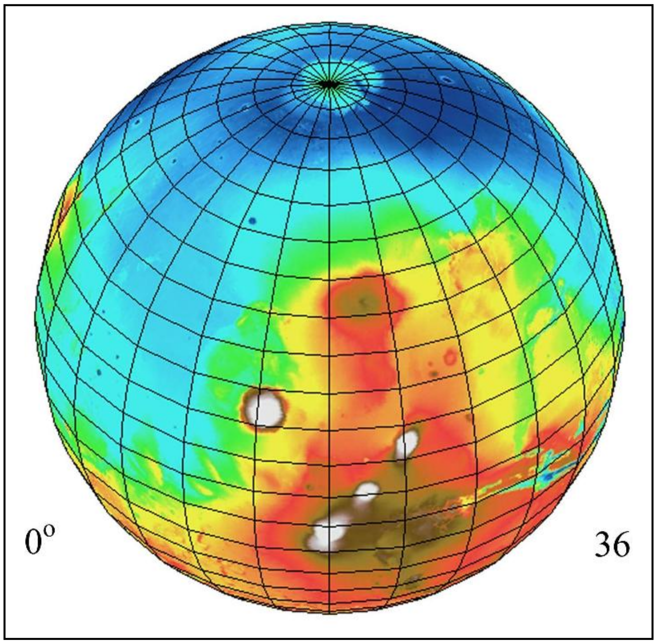
Peak 1 = 53 milliRads/day x 1 days = 53 millirads
Peak 2 = 2866 millirads/day x 3 days = 8598 milliRads
Peak 3 = 90 milliRads/day x 1 days = 90 milliRads
Peak 4 = 1700 milliRads/day x 3 days = 5100 milliRads
Peak 5 = 70 milliRads/day x 1 days = 70 milliRads
Peak 6 = 140 milliRads/day x 0.5 days = 70 milliRads

The total dose is 13,981 milliRads. Since 1,000 milliRads = 1 Rad, the answer is 14.0 Rads. Convert this to Rems by multiplying by (2 Rem/1 Rad) to get **28 Rems.**

Problem 3 - Which radiation source, SPEs or cosmic rays, has the largest percentage contribution to an astronaut's total radiation exposure?

Answer: The total exposure was 10 + 14 = 24 rads. Cosmic rays contribute 100% x (10 Rads/24 Rads) = 42% while SPEs contribute 100% x (14 Rads/24 Rads) = 58%, so **SPEs seem to be slightly more significant if this data is typical of what astronauts will experience**.

Having a Hot Time on Mars!



Mars has virtually no atmosphere leaving its surface unprotected from solar and cosmic radiation.

This figure, created with the NASA, MARIE instrument on the Odyssey spacecraft orbiting Mars, shows the unshielded surface radiation dosages:

Color	Rem/yr
Brown	20
Orange	18
Yellow	16
Light blue	13
Dark blue	10

Astronauts landing on Mars will want to minimize their total radiation exposure during the 540 days they will stay on the surface. Assume that the Mars astronauts used improved post-Apollo spacesuit technology providing a shielding reduction of 1/8, and that the Mars Habitat provided a 1/20 radiation reduction.

Problem 1 - The typical, unshielded radiation dose on the surface of Earth for cosmic rays is about 0.040 Rems/yr. By what factor is the unshielded, minimum radiation exposure for Mars astronauts in excess of the normal terrestrial rates?

Problem 2 - The Mars explorers would like to spend 2 hours in spacesuits and the remaining 24-hours inside the Mars Habitat during each of the 540-days of exploration on Mars. What would be the approximate total dose for the astronauts in the 'dark blue' polar regions at the end of A) a single day? B) 1 Earth-year? C) the entire Mars visit?

Problem 3 - The total background+lifestyle dose on Earth at ground-level is about 360 milliRem/yr. How many extra years of radiation exposure will an astronaut accumulate exploring the surface of Mars rather than 'staying home'?

Answer Key

Problem 1 - The typical, unshielded radiation dose on the surface of Earth for cosmic rays is about 0.040 Rems/yr. By what factor is the unshielded, minimum radiation exposure for Mars astronauts in excess of the normal terrestrial rates?

Answer: The lowest mapped rates are about 10 Rem/yr, so this is about 10 Rem/0.040 Rem = 250-times higher than terrestrial ground rates.

Problem 2 - The Mars explorers would like to spend 2 hours in spacesuits and the remaining 24-hours inside the Mars Habitat during each of the 540-days of exploration on Mars. What would be the approximate total dose for the astronauts in the 'dark blue' polar regions at the end of A) a single day? B) 1 Earth-year? C) the entire Mars visit?

Answer: The dark blue region corresponds to 10 Rem/yr or 27 milliRem/day, assuming 1 Earth-year = 365 days. In terms of an hourly rate we have for 1 day = 24 hours that the dose rate is 1.1 milliRem/hr.

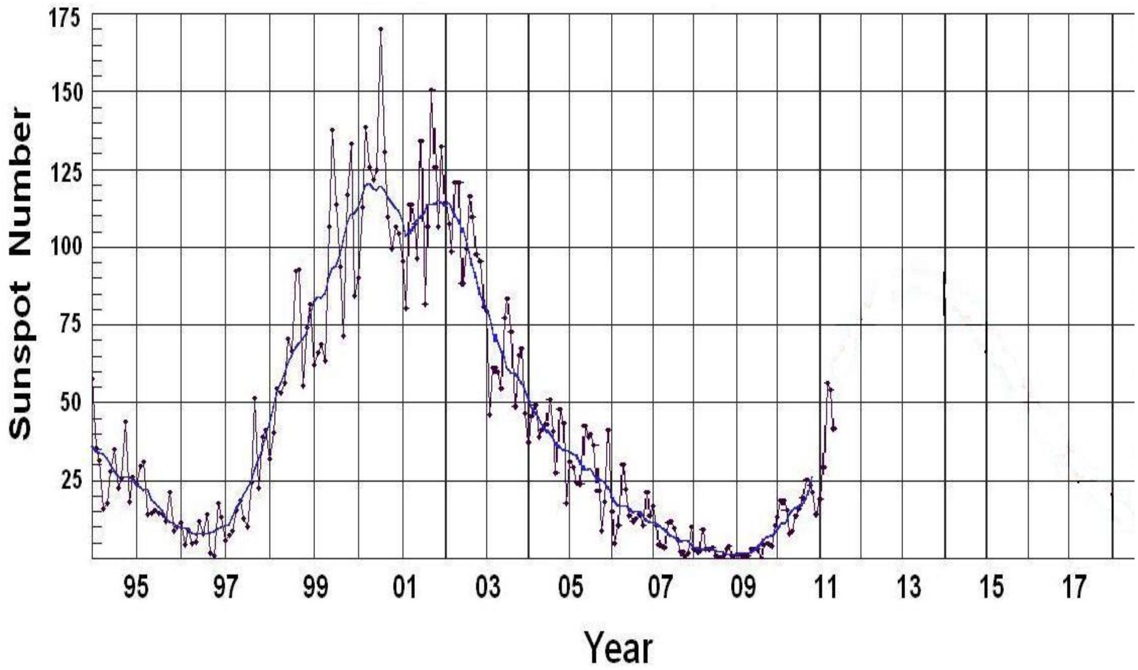
A) For the Mars Habitat, its shielding reduces the daily dose by 1/20 so for 22 hours the dose will be 1.1 milliRem/hr x (1/20) x 22 hrs = 1.21 milliRem. The spacesuit dose would be 1.1 milliRem/hr x (1/8) x 2 hrs = 0.28 milliRem ,so the total daily accumulated dose would be 1.21 + 0.28 = **1.49 milliRem/day**.

B) For one Earth-year the accumulated dose would be 1.49 milliRem/day x 365 days = **543 milliRem/yr or 0.54 Rem/yr.**

C) For 540-days, the total dose would be 1.49 milliRem/day x 540 days = **805 milliRem or 0.80 Rem.**

Problem 3 - The total background+lifestyle dose on Earth at ground-level is about 360 milliRem/yr. How many extra years of radiation exposure will an astronaut accumulate exploring the surface of Mars rather than 'staying home'?

Answer: If he spent 540-days on Earth, he would have accumulated 360 milliRem/yr x 540 days/365 days= 532 milliRem. On Mars the total accumulation would have been 805 milliRem for 540 days. The excess accumulation is just 805 milliRem - 532 milliRem = 273 milliRem. This equals 273/360 = **0.76 additional years**.



The above plot shows the annual averaged sunspot numbers for the period from January 1994 to May, 2011. The data shows the previous sunspot cycle (Number 23) and the beginnings of the current sunspot cycle (Number 24).

Problem 1 - About when (month and year) did Sunspot Cycle 23 begin?

Problem 2 - About when (month and year) did Sunspot Cycle 23 reach its maximum?

Problem 3 - What is the number of years between sunspot minima to the nearest tenth of a year?

Problem 4 - How long did Cycle 23 take to reach sunspot maximum?

Problem 5 - When (year, month) do you predict we will reach sunspot maximum during the next cycle (Cycle 24)?

Problem 6 - When (year, month) do you think the next sunspot minimum will occur after the peak of the current Cycle 24?

Answer Key

Problem 1 - When (month and year) did Sunspot Cycle 23 begin?

Answer: Around **July, 1996**

Problem 2 - When (month and year) did Sunspot Cycle 23 reach its maximum?

Answer: Around **July, 2000** and a second maximum near **September, 2001**

Problem 3 - What is the number of years between sunspot minima to the nearest tenth of a year?

Answer: The first minimum was on July, 1996 and the current minimum seems to be around January 2009 so the difference is 2009.0 - 1996.58 = **12.4 years**.

Problem 4 - How long did Cycle 23 take to reach sunspot maximum?

Answer: The first maximum occurred on July 2000, the minimum was July 1996, so it took **4 years**.

Problem 5 - When (year, month) do you predict we will reach sunspot maximum during the next cycle (Cycle 24)?

Answer: If we add 4 years to the current minimum on January, 2009 we get **January, 2013**.

Problem 6 - When (year, month) do you think the next sunspot minimum will occur?

Answer: From our answer to Problem 3, if we add 12.4 years to January, 2009 we get 2009.00 + 12.4 = 2021.4 or about **June, 2021**.

Note: Astronomers consider Cycle 23 to be unusual compared to the average 11-year cycle. If we select an 11-year average cycle length, the next sunspot minimum could be around 2020 rather than 2021.

Sunspot Cycles Since 1900

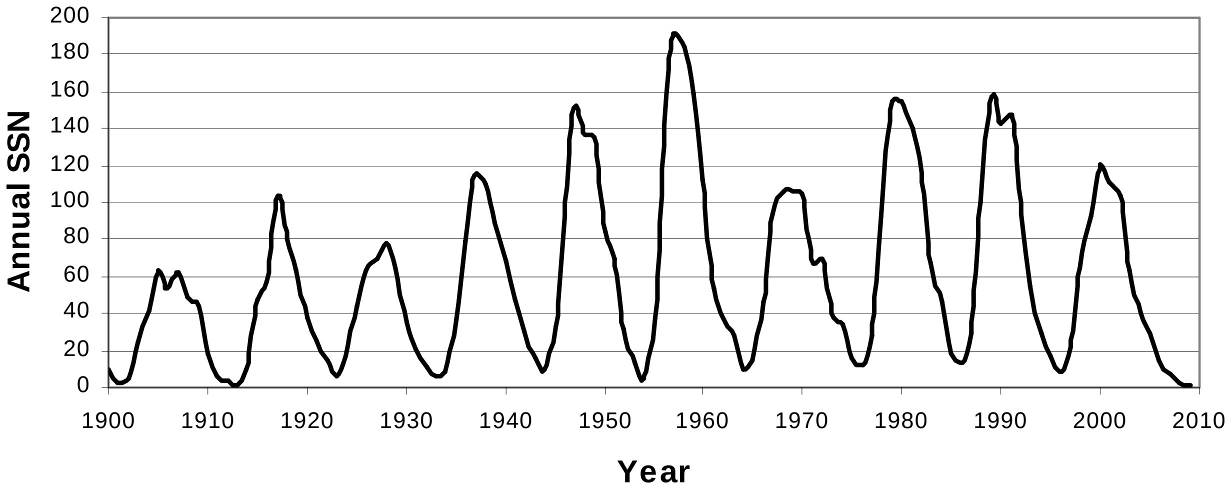
Table of Annual-averaged Sunspot Numbers Since 1900

Year	SSN	Year	SSN	Year	SSN	Year	SSN
1900	9	1928	78	1956	142	1984	46
1901	3	1929	65	1957	190	1985	18
1902	5	1930	36	1958	185	1986	13
1903	24	1931	21	1959	159	1987	29
1904	42	1932	11	1960	112	1988	100
1905	63	1933	6	1961	54	1989	158
1906	54	1934	9	1962	38	1990	142
1907	62	1935	36	1963	28	1991	146
1908	49	1936	80	1964	10	1992	94
1909	44	1937	114	1965	15	1993	55
1910	19	1938	110	1966	47	1994	30
1911	6	1939	89	1967	94	1995	18
1912	4	1940	68	1968	106	1996	9
1913	1	1941	47	1969	106	1997	21
1914	10	1942	31	1970	105	1998	64
1915	47	1943	16	1971	67	1999	93
1916	57	1944	10	1972	69	2000	120
1917	104	1945	33	1973	38	2001	111
1918	81	1946	93	1974	34	2002	104
1919	64	1947	152	1975	15	2003	64
1920	38	1948	136	1976	13	2004	40
1921	26	1949	135	1977	27	2005	30
1922	14	1950	84	1978	93	2006	15
1923	6	1951	69	1979	155	2007	8
1924	17	1952	31	1980	155	2008	3
1925	44	1953	14	1981	140	2009	2
1926	64	1954	4	1982	116		
1927	69	1955	38	1983	67		

In 1843, the German astronomer Samuel Schwab plotted the number of sunspots on a graph and discovered that the number of sunspots on the sun was not the same every year, but goes through a cyclical increase and decrease over time. The table above gives the average number of sunspots (SSN) detected each year since 1900.

Problem 1 - Graph the data in the table over the domain [1900, 2009] and range [0,200]. How many sunspot cycles can you count over this time interval?

Problem 2 - What is the average period of the sunspot cycle during this time interval?



Problem 1 - Graph the data in the table over the domain [1900, 2009] and range [0,200]. How many sunspot cycles can you count over this time interval?

Answer: **There are 10 complete cycles**.

Problem 2 - What is the average period of the sunspot cycle during this time interval?

Answer: The time interval is 109 years during which 10 cycles occur for an average period of **10.9 years**.

Note: Additional sunspot data can be found at

Spaceweather.com **http://www.spaceweather.com/java/archive.html**

NASA Marshall Spaceflight Center **http://solarscience.msfc.nasa.gov/SunspotCycle.shtml**

NOAA Space Weather Prediction Center

http://www.swpc.noaa.gov/ftpmenu/warehouse.html
Select year from list, select file 'DSD.txt' and open. Column 5 gives average SSN for given day.

Cosmic Rays and the Sunspot Cycle

Year	SSN	Flux	Year	SSN	Flux	Year	SSN	Flux
1950	84	93	1970	105	86	1990	142	76
1951	69	94	1971	67	88	1991	146	80
1952	31	95	1972	69	98	1992	94	86
1953	14	96	1973	38	96	1993	55	94
1954	4	98	1974	34	100	1994	30	96
1955	38	100	1975	15	97	1995	18	98
1956	142	98	1976	13	99	1996	9	99
1957	190	94	1977	27	100	1997	21	99
1958	185	80	1978	93	96	1998	64	100
1959	159	84	1979	155	90	1999	93	96
1960	112	82	1980	155	89	2000	120	88
1961	54	84	1981	140	84	2001	111	86
1962	38	88	1982	116	88	2002	104	88
1963	28	92	1983	67	80	2003	64	86
1964	10	96	1984	46	90	2004	40	86
1965	15	98	1985	18	92	2005	30	94
1966	47	98	1986	13	96	2006	15	96
1967	94	93	1987	29	98	2007	8	98
1968	106	90	1988	100	94	2008	3	100
1969	106	88	1989	158	84			

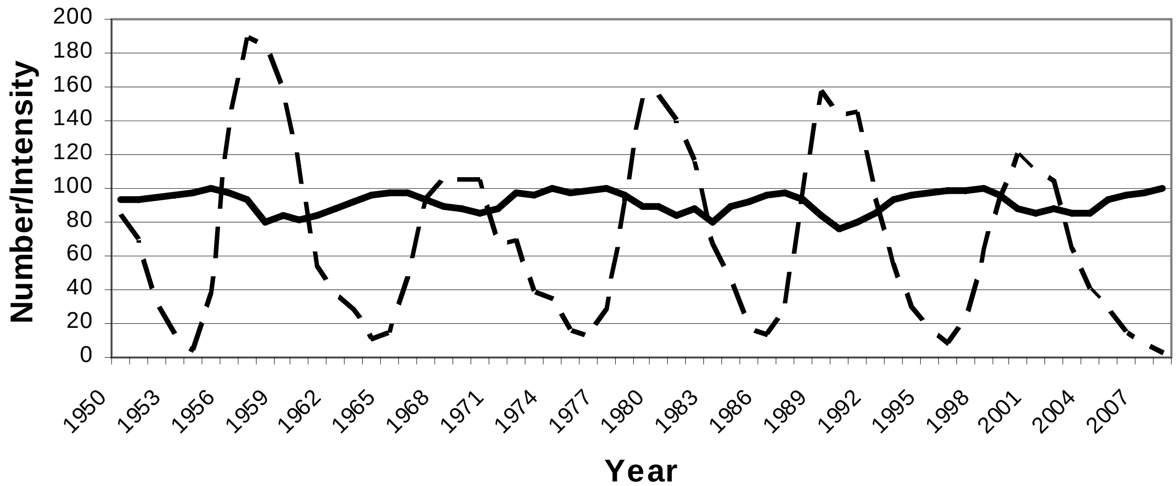
Cosmic rays are high-energy particles that enter our solar system from distant sources in the Milky Way galaxy and beyond. These particles are a radiation hazard for satellite electronics and for astronauts exposed to them for prolonged periods of time. The table above presents the flux of the cosmic rays measured by instruments located in Climax, Colorado during the period from 1950 to 2008, along with the annual sunspot counts. For example, in 1967, the annual average sunspot number was 106, and the cosmic ray flux was 93 units.

Problem 1 - On the same graph, plot the sunspot numbers and the cosmic ray intensities.

Problem 2 - What do you notice about the relationship between cosmic rays and sunspots?

Problem 3 - If you were planning a 1-year trip to Mars, what time would you make your journey relative to the sunspot cycle?

Problem 1 - On the same graph, plot the sunspot numbers and the cosmic ray intensities. Answer: **See below.**



Problem 2 - What do you notice about the relationship between cosmic rays and sunspots?
Answer: **When the sunspot number is highest, the cosmic ray intensity is lowest. The sunspot number peaks (maxima) match up with the cosmic ray valleys (minima).**

Problem 3 - If you were planning a 1-year trip to Mars, what time would you make your journey relative to the sunspot cycle?
Answer: **You would probably want to make the journey during sunspot maximum conditions when the cosmic ray intensity is lowest. This will reduce your total accumulated radiation dosage during the 1-year trip by 20%.**

Histogram of Halo CME Speeds: 1996-2008

Speed (km/s)	N	Speed (km/s)	N	Speed (km/s)	N
0	1	1000	20	2000	9
100	6	1100	22	2100	3
200	8	1200	14	2200	4
300	19	1300	21	2300	3
400	38	1400	13	2400	4
500	33	1500	14	2500	4
600	33	1600	11	2600	2
700	25	1700	12	2700	0
800	30	1800	9	2800	1
900	30	1900	7		

During the past sunspot cycle, there were nearly 2,000 events, called coronal mass ejections (CMEs) in which the sun ejected huge clouds of plasma into space.

When some of these CMEs are directed at Earth, they appear as an expanding halo of light around the disk of the sun. These 'Halo CMEs' typically arrive within a few days and cause disturbances in Earth's magnetic field, called geomagnetic storms.

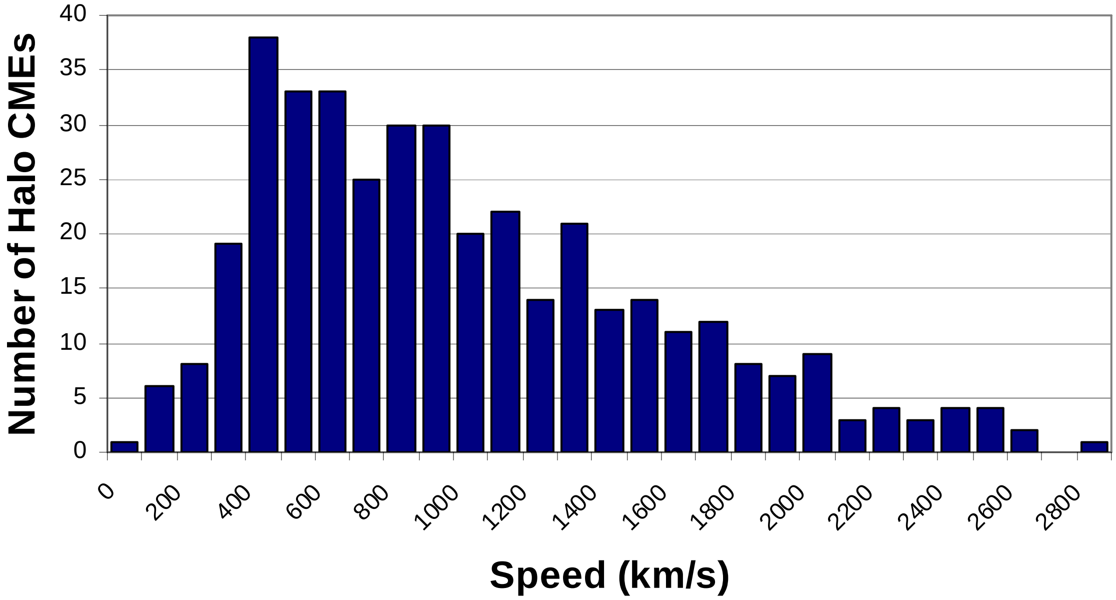
The arrival time is determined by the transit speed. The table above gives the speeds for a sample of Earth-directed CMEs. For example, there were 14 CMEs detected with speeds of 1500 km/s.

Problem 1 - Create a histogram of the frequency data in the table.

Problem 2 - For this distribution of CME speeds, what is A) the mean speed? B) the median speed?

Problem 3 - If the distance to the sun from Earth is 150 million kilometers, what is the average transit time, in days, represented by the histogram of CME speeds?

Problem 1 - Create a histogram of the frequency data in the table.



Problem 2 - For this distribution of CME speeds, what are the A) mean speed? B) median speed?

Answer: A) From the table, the average speed is found by the sun of the products of the speeds and Ns divided by the total number of tabulated CMEs which equals 395 events, so Va = (388700/395) so **Va = 984 km/sec**.
B) The median speed is the speed for which half of the events are below and half are above. From the table, N = 395/2 = 197, so **Vm = 800 km/sec**.

Problem 3 - If the distance to the sun from Earth is 150 million kilometers, what is the average transit time, in days, represented by the histogram of CME speeds?

Answer: T = 150 million km / 984 km/s so T = 152,632 seconds which is about 42.4 hours or **T = 1.8 days**.

Fastest Halo CME Speeds by Year and Month

Table of Fast CMEs between 1996 - 2006

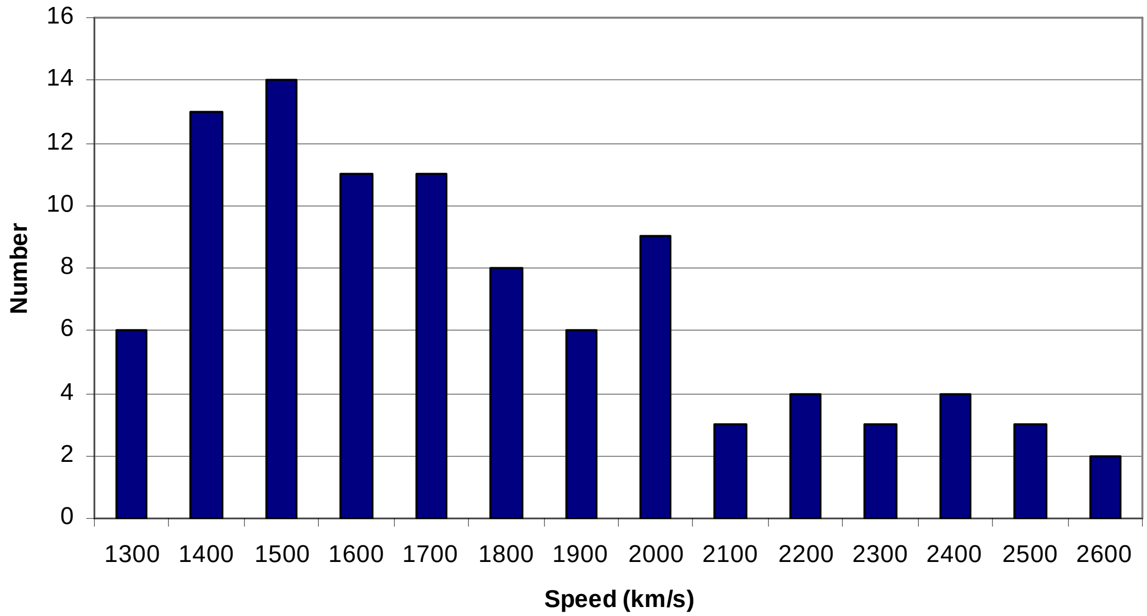
Year	Month	Speed	Year	Month	Speed	Year	Month	Speed	Year	Month	Speed
2004	11	3387	2002	7	2047	1999	6	1772	2001	10	1537
2005	1	2861	2003	11	2036	2004	11	1759	2005	7	1527
2003	11	2657	2003	10	2029	2002	3	1750	2003	11	1523
2000	5	2604	2005	1	2020	1998	12	1749	2001	1	1507
2003	11	2598	2003	11	2008	2002	9	1748	2001	12	1506
2005	1	2547	2004	11	2000	2001	6	1701	1998	11	1505
2005	7	2528	1998	3	1992	2002	10	1694	1999	4	1495
2000	11	2519	2005	7	1968	1999	5	1691	2002	1	1492
2001	4	2465	2002	7	1941	2005	5	1689	2003	10	1484
2003	10	2459	2005	8	1929	2005	6	1679	2001	4	1475
2001	4	2411	2005	9	1922	2000	7	1674	2005	7	1458
2001	9	2402	2002	8	1913	2005	9	1672	2004	7	1444
2002	4	2393	2005	9	1893	2003	11	1661	2001	11	1443
2005	8	2378	2005	9	1866	2005	7	1660	2001	11	1437
2005	9	2326	2002	11	1838	2002	7	1636	2001	8	1433
2002	7	2285	2003	5	1835	1998	4	1618	2002	3	1429
2005	9	2257	2003	6	1813	2005	8	1600	2005	7	1423
2003	11	2237	2001	11	1810	2000	5	1594	2001	6	1407
2001	12	2216	2005	8	1808	2002	8	1585	2001	10	1405
2002	7	2191	1998	6	1802	1999	5	1584	1998	3	1397
2002	10	2115	1998	11	1798	2001	8	1575	2001	4	1390
2005	7	2115	2002	1	1794	2002	5	1557	1999	7	1389
2005	1	2094	2005	7	1787	1997	11	1556	1998	4	1385
2003	6	2053	2000	5	1781	2000	9	1550	2005	9	1384
2005	1	2049	2001	12	1773	2005	7	1540	2005	2	1380

Coronal Mass Ejections (CMEs) can leave the solar surface at many different speeds as shown in the table above. This table gives the speeds in km/s ordered from fastest to slowest, of the Top-100 CMEs seen during the last sunspot cycle between 1996-2008. For example, during January, 2005 a CME was detected with a speed of 2094 km/s.

Problem 1 - Create a histogram of the CME speeds using bins that are 100 km/sec wide over the domain of speeds [1300, 2600].

Problem 2 - What is the: A) Average speed? B) Median speed? C) Mode speed?

Problem 3 - If the transit time to Earth is 42 hours for a CME traveling at a speed of 1,000 km/s, to the nearest hour, what is A) the range of speeds spanned by this



Problem 1 - Create a histogram of the CME speeds using bins that are 100 km/sec wide over the domain of speeds [1300, 2600]. Answer: See above.

Problem 2 - What is the: A) Average speed? B) Median speed? C) Mode speed?
Answer:
A) The average speed is found by adding all 100 speeds and dividing by 100. The answer is **<V> = 1,851 km/sec**.
B) The median speed is the speed for which half of the CME speeds are below and half are above the value. The table is ranked from fastest to slowest so CME #50 will be close to the median speed for this 'even' numbered set. **Vm = 1,773 km/sec**.
C) The mode speed is the most frequently occurring speed in the sample which is **V = 2,115 km/sec**.

Problem 3 - If the transit time to Earth is 42 hours for a CME traveling at a speed of 1,000 km/s, to the nearest hour, what is A) the range of speeds spanned by this complete sample of 100 CMEs? B) The average transit time of a CME?

Answer: A) The range is from 1,380 to 3,387 km/sec B) so by scaling we get 42 x (1000/1380) = 30 hours for the slowest and 42 x (1000/3387) = 12 hours. the average transit time is T = 42 x (1000/1851) = **23 hours**.

Estimating Halo CME Arrival Times

Speed	Distance from the Sun in Astronomical Units										
(km/s)	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
300	139	153	167	181	194	208	222	236	250	264	278
400	104	115	125	135	146	156	167	177	188	198	208
500	83	92	100	108	117	125	133	142	150	158	167
600	69	76	83	90	97	104	111	118	125	132	139
700	60	65	71	77	83	89	95	101	107	113	119
800	52	57	63	68	73	78	83	89	94	99	104
900	46	51	56	60	65	69	74	79	83	88	93
1000	42	46	50	54	58	63	67	71	75	79	83
1100	38	42	45	49	53	57	61	64	68	72	76
1200	35	38	42	45	49	52	56	59	63	66	69
1300	32	35	38	42	45	48	51	54	58	61	64
1400	30	33	36	39	42	45	48	51	54	57	60
1500	28	31	33	36	39	42	44	47	50	53	56
1600	26	29	31	34	36	39	42	44	47	49	52
1700	25	27	29	32	34	37	39	42	44	47	49
1800	23	25	28	30	32	35	37	39	42	44	46
1900	22	24	26	29	31	33	35	37	39	42	44
2000	21	23	25	27	29	31	33	35	38	40	42
2100	20	22	24	26	28	30	32	34	36	38	40
2200	19	21	23	25	27	28	30	32	34	36	38
2300	18	20	22	24	25	27	29	31	33	34	36
2400	17	19	21	23	24	26	28	30	31	33	35
2500	17	18	20	22	23	25	27	28	30	32	33
2600	16	18	19	21	22	24	26	27	29	30	32
2700	15	17	19	20	22	23	25	26	28	29	31
2800	15	16	18	19	21	22	24	25	27	28	30
2900	14	16	17	19	20	22	23	24	26	27	29
3000	14	15	17	18	19	21	22	24	25	26	28

The shaded values in the table above give the arrival times (in hours) to the various distances in Astronomical Units (AUs), given the speed of the CME indicated in the first column. '1 AU' is the average distance from Earth to the sun of 150 million km.

Problem 1 - Suppose that the planet Earth and Mars are in opposition, which means that a straight line can be drawn from the center of the sun directly through the centers of Earth and Mars. Astronomers at Earth detect a CME leaving the sun at a speed of 1500 km/sec. When will this CME arrive at Earth and how long afterwards will it arrive at Mars located at a distance of 1.5 AU?

Problem 2 - A CME leaves the sun at a speed of 900 km/sec on July 4, 2015 at 13:00 UT. On what dates and times will it arrive at A) Earth? B) Mars? C) An asteroid located at 1.9 AU?

Problem 1 - Suppose that the planet Earth and Mars are in opposition, which means that a straight line can be drawn from the center of the sun directly through the centers of Earth and Mars. Astronomers at Earth detect a CME leaving the sun at a speed of 1500 km/sec. When will this CME arrive at Earth (1.0 AU) and how long afterwards will it arrive at Mars located at a distance of 1.5 AU?

Answer: From the table, look at the row for '1500' in Column 1 and under '1.0' AU the time for arrival at Earth is about **26 hours**. In the column for Mars at '1.5' the arrival time is 39 hours, so it takes **13 additional hours for the CME to arrive at Mars**.

Problem 2 - A CME leaves the sun at a speed of 900 km/sec on July 4, 2015 at 13:00 UT. On what dates and times will it arrive at A) Earth? B) Mars? C) An asteroid located at 1.9 AU?

Answer: A) The transit time to Earth is 46 hours so adding 46 hours to the given date and time we get an additional 1 day and 22 hours so July 4, 2015 at 13:00 + 1 day and 22:00 gives July 5, 2015 at 35:00 which becomes **July 6, 2015 at 11:00 UT**.

B) The transit time is 69 hours or 2 days + 21 hours, which gives July 6, 2015 and 34:00 or **July 7, 2015 at 10:00 UT**.

C) The transit time is 88 hours or 3 days and 16:00 which becomes July 7, 2015 at 29:00 or **July 8, 2015 at 05:00 UT**.

Solar Flares and the Sunspot Cycle

Year	C-class	M-class	X-class
1996	76	4	1
1997	288	20	3
1998	1198	96	14
1999	1860	170	4
2000	2265	215	17
2001	3107	311	20
2002	2319	219	12
2003	1315	160	20
2004	912	122	12
2005	578	103	18
2006	150	10	4
2007	73	10	0
2008	8	1	0

Solar flares are the most dramatic explosions on the sun, which have been known for some time. An average-sized flare can release more energy in a few hours than thousands of hydrogen bombs exploding all at once.

Solar flares do not happen randomly, but like many other solar phenomena follow the rise and fall of the sunspot cycle.

The table to the left is a tally of the number of C, M and X-class flares identified during each year of the previous sunspot cycle.

Problem 1 - During the entire sunspot cycle, how many solar flares occur?

Problem 2 - What percentage of solar flares during an entire sunspot cycle are A) C-class? B) M-class? C) X-class?

Problem 3 - During a single week, how many flares of each type would the sun produce during A) Sunspot maximum in the year 2001? B) Sunspot minimum during the year 1996?

Problem 4 - During sunspot maximum, what is the average time in hours between flares for, A) C-class? B)M-class? and C) X-class? (Hint: 1 year = 8,760 hours)

Problem 5 - Do as many flares occur in the time before sunspot maximum (1996-2000) as after sunspot maximum (2002-2008) for A) C-class? B) M-class? C) X-class?

Problem 1 - During the entire sunspot cycle, how many solar flares occur?
Answer: The sum of all the flares in the table is **15,715**.

Problem 2 - What percentage of solar flares during an entire sunspot cycle are A) C-class? B) M-class? C) X-class?
Answer: A) C-class = 100% x (14149/15715) = **90%**
B) M-class = 100% x (1441/15715) = **9%**
C) X-class = 100% x (14149/15715) = **1%**

Problem 3 - During a single week, how many flares of each type would the sun produce during A) Sunspot maximum in the year 2001? B) Sunspot minimum during the year 1996?
Answer: A) C-type = 3107/52 = **60**
M-type = 311/52 = **6**
X-type = 20/52 = **0.4**

B) C-type = 76/52 = **1.4**
M-type = 4/52 = **0.08**
X-type = 1/52 = **0.02**

Problem 4 - During sunspot maximum, what is the average time in hours between flares for, A) C-class? B)M-class? and C) X-class? (Hint: 1 year = 8,760 hours)
Answer: C-class = 1 year/3107 flares x (8760 hours/year) = **2.8 hours/flare**.
M-class = 1 year/311 flares x (8760 hours/year) = **28 hours/flare**. (1 day)
X-class = 1 year/20 flares x (8760 hours/year) = **438 hours/flare**. (18 days)

Problem 5 - Do as many flares occur in the time before sunspot maximum (1996-2000) as after sunspot maximum (2002-2008) for A) C-class? B) M-class? C) X-class?

Answer: Between 1996-2000 there were 6,231 and between 2001-2008 there were 6,046 so although the numbers are nearly the same, there were slightly fewer flares after sunspot maximum.

Note: In statistics, the sampling error is n = $(6231)^{1/2}$ = 79, so the range of random variation for 1996-2000 is between 6231+79 and 6231-79 or [6151, 6310] for 2002-2008 we have $(6046)^{1/2}$ = 78, so the range of random variation for 2002-2008 is between 6046+78 and 6046-78 or [5968, 6124]. Because of this sampling uncertainty, the counts between each side of solar maximum are statistically similar. They do not differ by more than 3-sigma (3x78 = 234) which means they are the same to better than 98% certainty.

M-flares as Predictors of X-flares

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
-7		2		0	0	0	2	0		0					4			2			2	2	0	0	0	0		0
-6		5	0	1	0	1	1	0		0					0			2			1	2	0	0	0	0		0
-5		3	1	0	0	0	0	0		0	0	0			0	0	0	4	2	0	0	1	0	0	0	0		0
-4	0	3	0	0	0	0	4	0	7	0	0	0		0	0	0	0	2	1	0	2	1	0	0	0	0	0	0
-3	0	4	0	0	2	0	2	0	5	1	0	0	1	0	1	0	1	3	0	0	1	0	0	1	1	1	1	0
-2	0	1	3	0	2	0	2	0	2	5	0	0	2	0	0	0	1	2	3	0	0	0	0	0	0	0	0	0
-1	1	1	5	4	1	0	4	1	4	2	0	0	7	2	1	0	0	4	3	1	0	0	3	1	0	1	1	0
0	0	2	4	6	0	4	0	4	0	0	1	2	3	2	2	0	1	1	0	2	1	0	2	0	0	0	0	2

The table above lists the number of M-class flares that occurred on the sun in the 7 days preceding the appearance of an X-class flare for 28 separate solar events. For example ,during sunspot Cycle 13 (column 14 entry for '13') there were 7 M-class flares counted during the first day after an X-class flare (row 8 entry for '-1').

Problem 1 - For each day prior to an X-class flare, what is the average number of M-class flares that occurred?

Problem 2 - What is the standard deviation (sigma) for the average value during each day?

Problem 3 - Graph the average number of M-class flares counted for each day including the range determined by 1-sigma error bars.

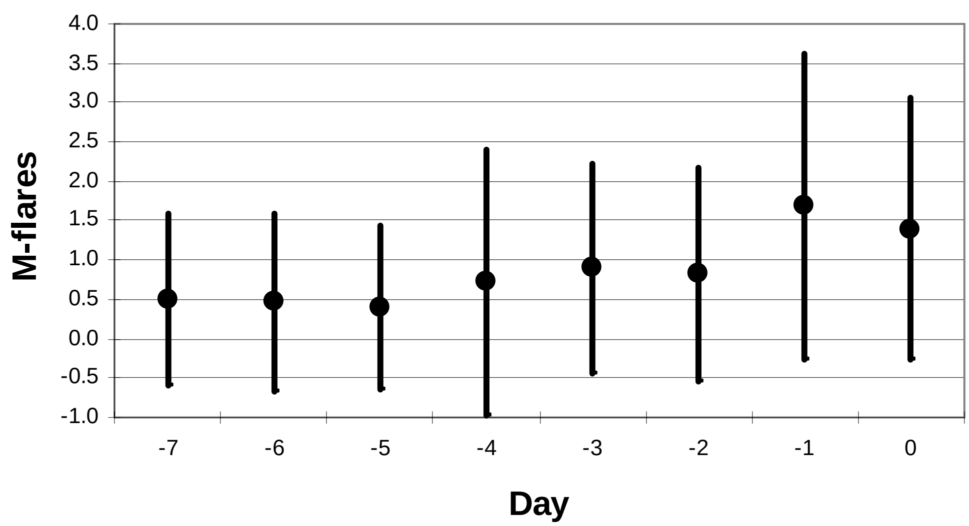
Problem 4 - Is the M-flare activity a good predictor of whether an X-class flare will occur or not?

Problem 1 - For each day prior to an X-class flare , what is the average number of M-class flares that occurred? Answer: **See table below.**

Problem 2 - What is the standard deviation (sigma) for the average value during each day?
Answer: **See table below.**

Day	Average	Sigma
-7	0.5	1.0
-6	0.5	1.1
-5	0.4	1
-4	0.7	1.6
-3	0.9	1.3
-2	0.8	1.3
-1	1.7	1.8
0	1.4	1.6

Problem 3 - Graph the average number of M-class flares counted for each day including the range determined by 1-sigma error bars. Answer: **See below.**



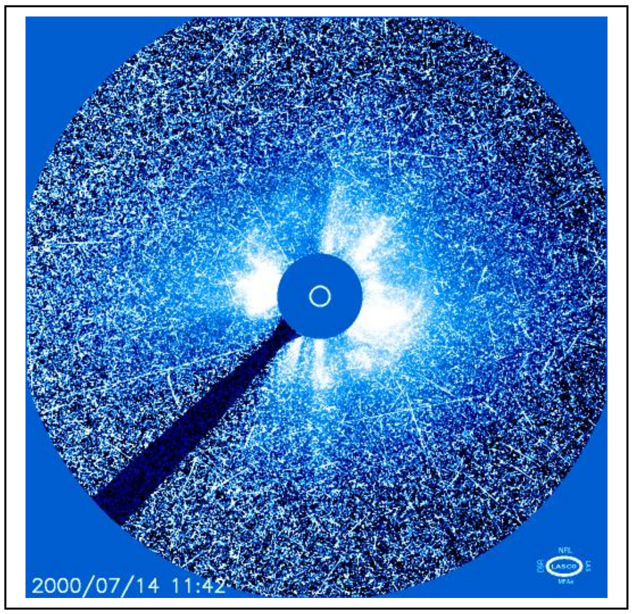
Problem 4 - Is the M-flare activity a good predictor of whether an X-class flare will occur or not? **Answer: The averages show a weak trend upwards, but the 1-sigma error bars are so large that the apparent trend is not statistically significant. All of the daily averages are within 1-sigma of each other.**

Time Profile of Solar Proton Event Dose Rate

Time (hrs)	Intensity (Counts)
0	40
4	10000
8	40000
12	35000
16	33000
20	25000
24	20000
28	15000
32	12000
36	10000
40	8000
44	6000
48	5000
52	4000
56	3000
60	2500
64	2200
68	2000
72	1500
76	1200
80	1000
84	600
88	400
92	250
96	200
100	180

The SOHO satellite is capable of measuring the intensity of high-energy protons emitted during a SPE using the CELIAS Proton Monitor developed by solar physicists the University of Maryland. The table on the left gives the recorded intensity for an SPE detected on April 21, 2002 which had a peak intensity of 2,520 particles/cm^2/sec.

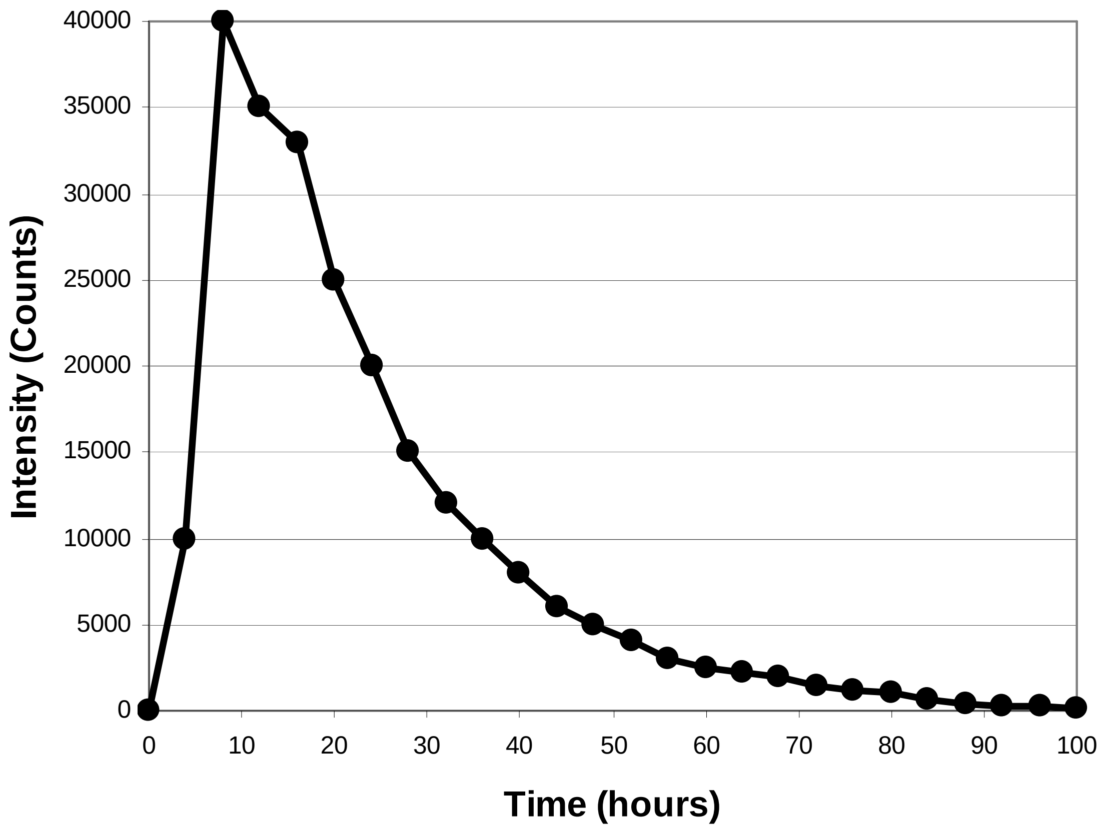
The figure below shows the result of an SPE on the imaging electronics of the SOHO satellite located 150 million kilometers from the sun. The white dots and streaks are caused by the high-energy protons striking the pixels and causing data errors.



Problem 1 - Graph the time history of the emission from this Solar Proton Event.

Problem 2 - The ground-level normal background radiation dose rate is about 0.05 milliRem/hour. Suppose that for an astronaut working inside a shielded spacecraft that the peak radiation dose rate from this event was 10 milliRem/hour. How long after the start of this SPE will the radiation dose rate fall below normal levels?

SPE light curve Courtesy University of Maryland   SOHO/Celias Proton Monitor
http://umtof.umd.edu/pm/flare/flare_figs.HTML



Problem 1 - Graph the time history of the emission from this Solar Proton Event.
Answer: **See above.**

Problem 2 - The ground-level normal background radiation dose rate is about 0.05 milliRem/hour. Suppose that for an astronaut working inside a shielded spacecraft that the peak radiation dose rate from this event was 10 milliRem/hour. How long after the start of this SPE will the radiation dose rate fall below normal levels?

Answer: Peak counts = 40,000 which equals 10 milliRem, so for 0.05 milliRem we have the proportion   0.05/10 x 40000 = 200 counts. This level occurs **96 hours after the start of the storm, so you have to wait nearly 3 days!**

Number of SPEs During Sunspot Cycles

Yr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	5											5	5		4			4					
2											2	4					3						
3																							
4						6				19							2					4	
5				3									2										4
6													8			2			2				3
7									3				11		2	5			9				
8												3	8	3									3
9	4			6					9	7		4	3	3						5			
10		5		4													3						
11										2													
12																							
13						3																	

Note: The columns indicate the corresponding sunspot cycles from 1 to 23. The calendar year for 'Year 1' for each cycle is as follows:1755, 1765, 1775, 1785, 1798, 1810, 1823, 1833, 1843, 1856, 1867, 1878, 1889, 1901, 1913, 1923, 1933, 1944, 1954, 1964, 1975, 1986, 1996

The table above gives the number of Solar Proton Events (SPEs) detected since 1751 (Cycle 1) through the end of the last sunspot cycle in 2008 (Cycle 23). The data for Cycle 1 - 22 were obtained by Dr. Robert McCracken in a study of ice cores from Greenland and Antarctica, which recorded the atmospheric changes caused by the most intense SPEs during each year. For example, during Cycle 19, and the 7th year of that cycle (1954+6 = 1960) there were 9 SPE events detected.

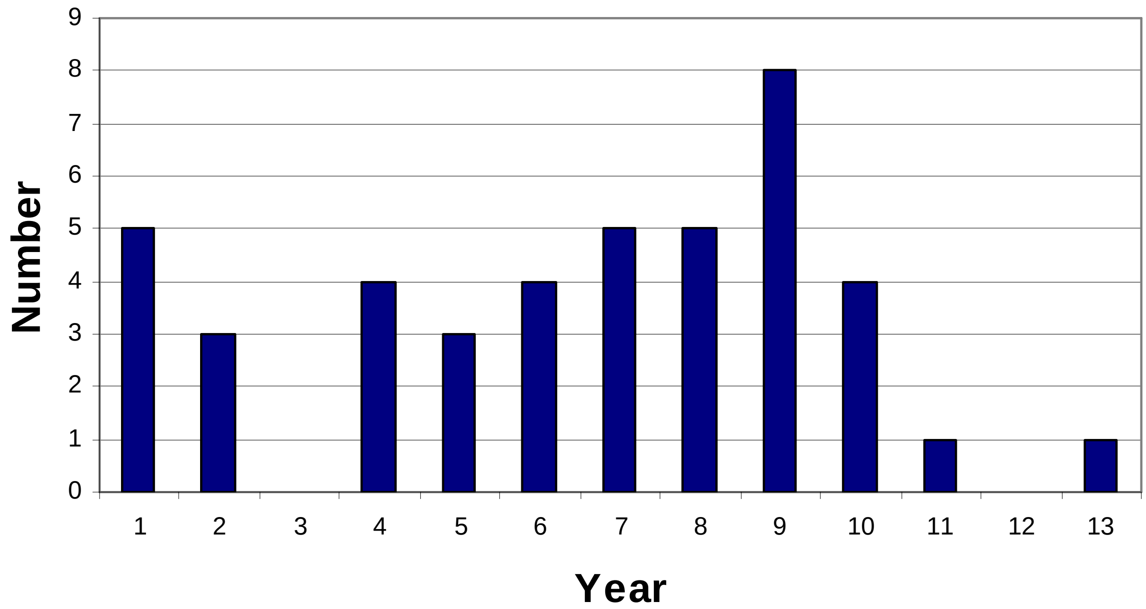
Although the ice core data was assembled chronologically as a continuous record of events since 1562, the above table folds the intensity of SPEs each year by the year of the sunspot cycle in which the SPE was recorded. The calendar year for 'Year 1' in the far-left column is given in the legend for the table.

Problem 1 - Create a histogram that tallies the number of SPEs occurring in each of the 13 years of the sunspot cycle. What is the total number of SPEs recorded for the 23 sunspot cycles?

Problem 2 - For each year in the average sunspot cycle, what is the percentage of SPEs that one expects to find?

Problem 3 - Which year of the sunspot cycle has the greatest historical percentage of SPEs?

Problem 1 - Create a histogram that tallies the number of SPEs occurring in each of the 13 years of the sunspot cycle. What is the total number of SPEs recorded for the 23 sunspot cycles?



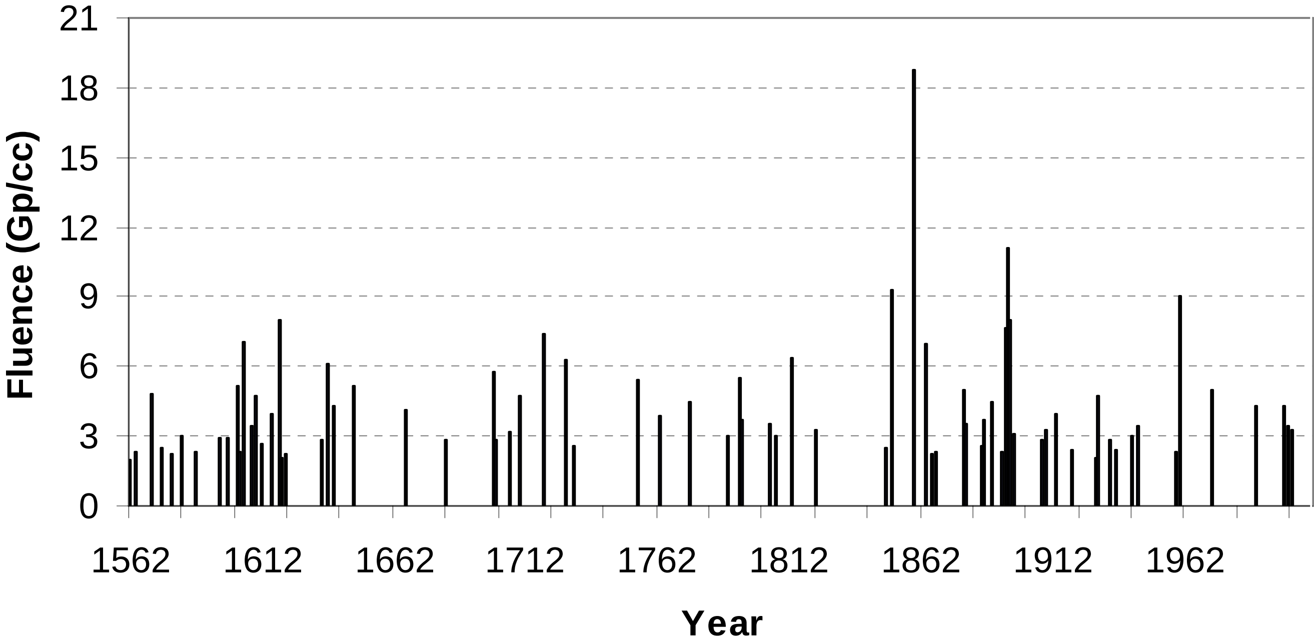
Answer: **Total = 43**

Problem 2 - For each year in the average sunspot cycle, what is the percentage of SPEs that one expects to find?

Answer:

Year	Number	Percent
1	5	12
2	3	7
3	0	0
4	4	9
5	3	7
6	4	9
7	5	12
8	5	12
9	8	19
10	4	9
11	1	2
12	0	0
13	1	2

Problem 3 - Which year of the sunspot cycle has the greatest historical percentage of SPEs?
Answer: **Year 9.**



In 1976, Dr. Robert McCracken at the University of Aldlaide studied ice cores from Greenland and Antarctica and discovered chemical anomalies in the atmospheric composition of the element beryllium. He later correlated these 'spikes' in the normal abundance with solar proton events (SPEs). The above graph shows the intensities of these SPEs between 1562 - 2003. The SPE intensity, called the fluence, is given in terms of the total number of particles an SPE delivered to one cubic centimeter (cc) of the atmosphere in units of 1 billion particles/cc (1 Gp/cc) .

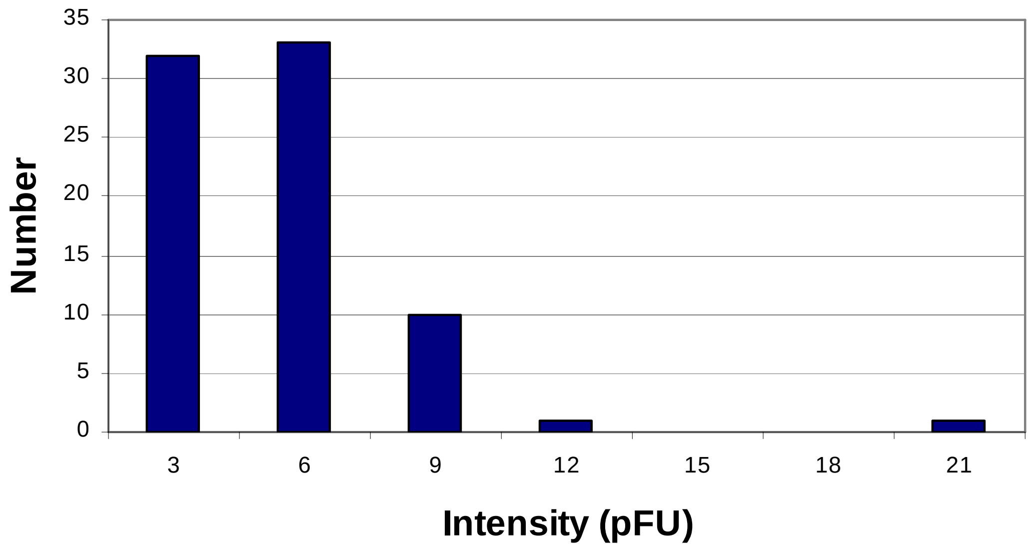
Problem 1 - Create a histogram by counting the number of SPEs with intensities in the following bin intervals: [0.1,3.0]; [3.1,6.0]; [6.1,9.0]; [9.1,12.0]; [12.1,15.0]; [15.1,21.0]

Problem 2 - A solar physicist detects an SPE. What is the probability, in percent, that it will be more intense than 6 Gp/cc?

Problem 3 - About how many events were stronger than 6.0 Gp/cc over the entire span of the data base?

Problem 4 - The total radiation exposure in milliRems for a shielded astronaut inside a space craft can be estimated using the conversion that 1 Gp/cc = 10 milliRem. About how many milliRems of total exposure would have occurred for each of the 4 SPEs since 1965?

Problem 1 - Create a histogram by counting the number of SPEs with intensities in the following bin intervals: [0.1,3.0]; [3.1,6.0]; [6.1,9.0]; [9.1,12.0]; [12.1,15.0]; [15.1,21.0]
Answer: Depending on how well the graph can be read, students should get numbers that are close to the following exact count:
[0.1,3.0]; N=32
[3.1,6.0]; N = 33
[6.1,9.0]; N = 10
[9.1,12.0]; N = 1
[12.1,15.0]; N= 0
[15.1,21.0]; N = 1



Problem 2 - A solar physicist detects an SPE. What is the probability, in percent, that it will be more intense than 6 Gp/cc?
Answer: The total number of SPEs in the data is 32+33+10+1+1 = 77. The number that are stronger than 6 Gp/cc is 12, so the probability is 100% x (12/77) = **16%**

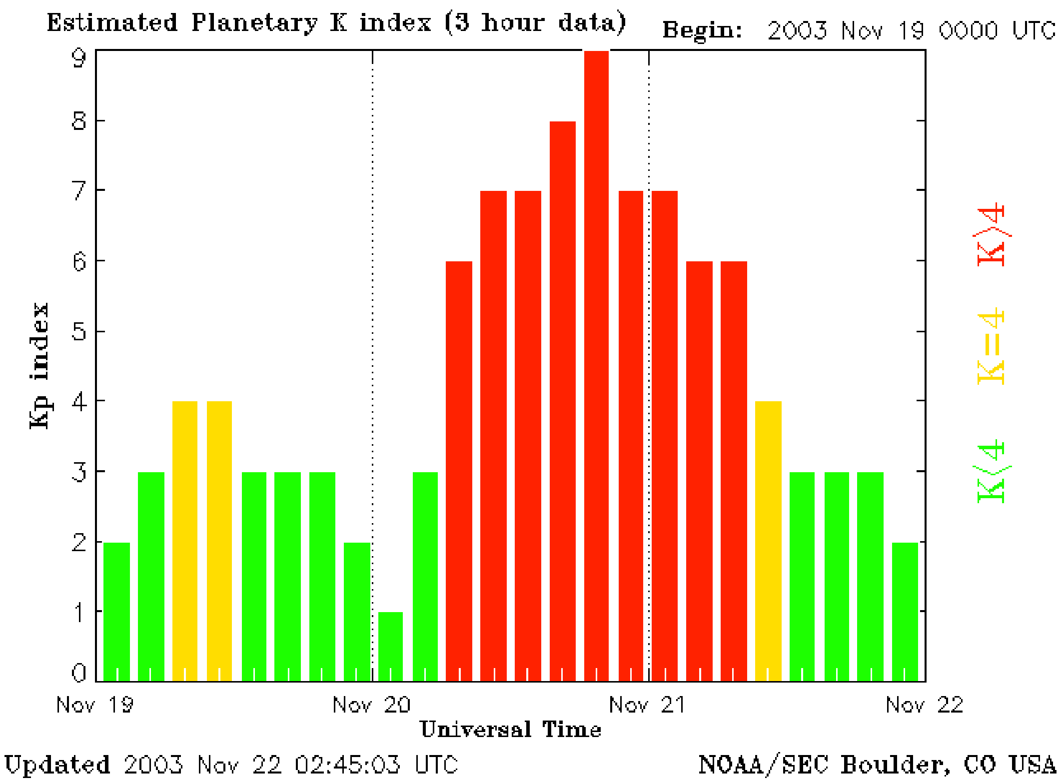
Problem 3 - About how many events were stronger than 6.0 Gp/cc over the entire span of the data base?
Answer: Students should be able to discern 12 events.

Problem 4 - During any 50-year period, how many events might you experience that would be more intense than 6.0 Gp/cc?

Answer: 12 events were detected over the period of 2003-1562 = 441 years, so the rate of events is R = 12/441 = 0.027 events/year. In 50 years, you will experience on average about 50x0.027 = 1.35 or **1 event!**

Note: An SPE with a fluence of 6.0 Gp/cc produces a shielded radiation dose to an astronaut of about 60 milliRem in a few hours. This is equal to about 60 days of normal radiation exposure on the ground!

Magnetic Storms and the Kp Index



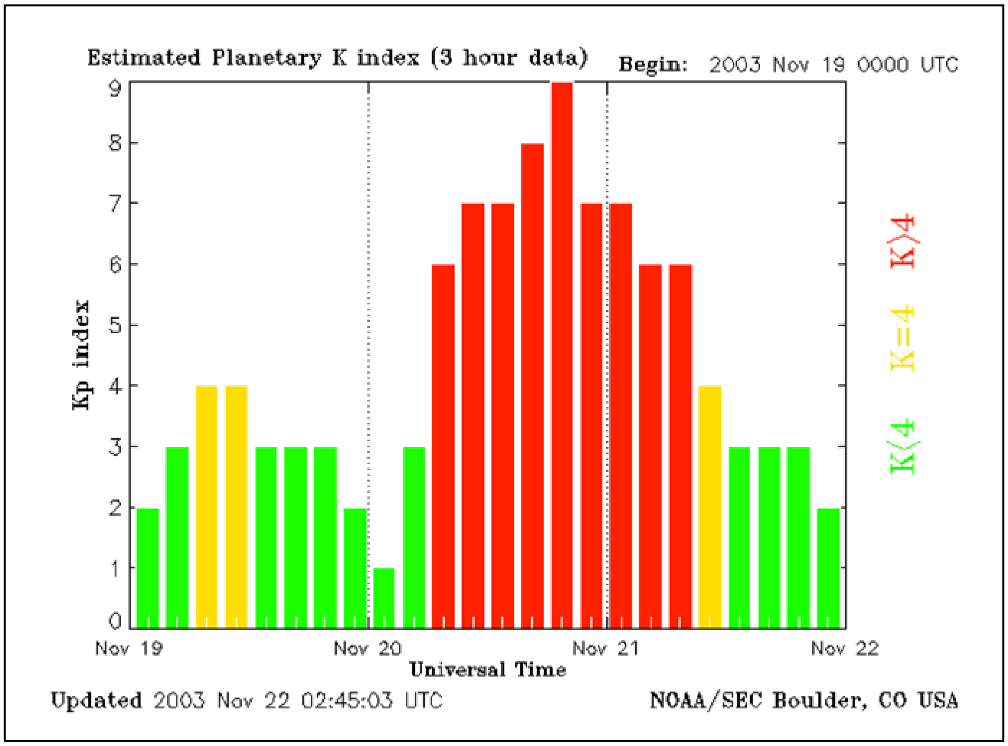
Satellites in orbit are affected by the build-up of electric charge, which can lead to equipment damage. The most intense periods of charge build-up occur during geomagnetic storms. To help scientists take a quick measure of Earth's magnetic storminess, Earth's magnetic field is measured at 13 selected 'magnetic observatories' around the world. The magnetic measurements are averaged together, and this average value is then reported every three hours as the **Kp Index**.

The bar graph above shows the changes in this index during the time of a major magnetic storm that began on November 20, 2003. Prior to the storm, Earth's magnetic field was in a typically disturbed state with variations between Kp 2 to 4. But after a coronal mass ejection (CME) plasma cloud collided with Earth's magnetic field, the variations jumped to Kp 7 and higher within a few hours. This particular storm caused spectacular Northern Lights seen all across North America and Northern Europe.

Problem 1 – If each bar is 3-hours wide, how long did the storm last above a level of Kp = 4?

Problem 2 – At what time did the storm reach its maximum Kp value?

Problem 3 - If on the date of this storm, New York City Local Time is 4 hours behind Universal Time, what Local Time time was it in New York during the height of the storm?



Problem 1 – If each bar is 3-hours wide, how long did the storm last?
Answer: The red portion of the bar graph which covers the most intense phase of the storm extends 9 bars or 9 x 3h = 27 hours!

Problem 2 – At what time did the storm reach its maximum Kp value?

Answer: This occurred at the bar which spans the times 19:00 to 21:00 UT so you can take the start time as 19:00 UT, or the end time 21:00 UT or the mid-point time of the bar of 20:30 UT.

Problem 3 - If New York City is 4 hours behind Universal Time, what time was it in New York during the height of the storm?

Answer: Taking the mid-time of 20:30 UT, the Eastern Standard Time in New York would be 20:30 – 4:00 = 16:30 EST or 4:30 PM.

Table of Event Frequencies for Cycle 23

	Flares (Class)			SPEs (pFU)				Halo
	C	M	X	10	100	1000	10000	CMEs
1996	76	4	1	1	1	0	0	1
1997	288	20	3	1	1	0	0	5
1998	1198	96	14	5	2	1	0	29
1999	1860	170	4	8	2	2	1	42
2000	2265	215	17	6	3	0	1	48
2001	3107	311	20	8	5	2	1	41
2002	2319	219	12	7	3	2	0	30
2003	1315	160	20	2	1	1	1	21
2004	912	122	12	3	1	1	1	87
2005	578	103	18	2	1	3	0	110
2006	150	10	4	0	1	1	0	33
2007	73	10	0	0	0	0	0	11
2008	8	1	0	0	0	0	0	12

The term 'solar storm' can refer to many different kinds of energetic phenomena including solar flares, Solar Proton Events (SPEs) and coronal mass ejections (CMEs).

Solar flares are the most well-known, and are classified according to their x-ray power as C, M or X, with X being the most powerful.

SPEs are classed according to the number of protons that pass through a surface area per second at Earth's orbit in units of particle Flux Units (where 1 pFU = 1 particle/cm^2/sec). SPEs with 10,000 pFUs or higher can be deadly to astronauts not properly shielded.

CMEs are billion-ton clouds of plasma ejected at high speed from the solar surface. When directed at Earth, they appear as an expanding 'halo' of particles surrounding the disk of the sun.

The table above gives the number of solar storms detected during each year of the previous solar activity cycle

Problem 1 - During sunspot maximum in 2001, what was the average number of hours you would have to wait between A) each of the three classes of X-ray flares? Each of the four classes of SPEs? and C) Each of the Halo CMEs? (Hint: There are 8,760 hours in 1 year)

Problem 2 - Assuming that Halo CMEs and X-class flares occur randomly over the year, what is the probability that during 2001 you will see both a Halo CME and an X-class flare on the same day?

Problem 1 - During sunspot maximum in 2001, what was the average number of hours you would have to wait between A) each of the three classes of X-ray flares? Each of the four classes of SPEs? and C) Each of the Halo CMEs? (Hint: There are 8,760 hours in 1 year)

Answer: From the table we have

	Flares (Class)			SPEs (pfu)				Halo
	C	M	X	10	100	1000	10000	CMEs
2001	3107	311	20	8	5	2	1	41

A) C-class flares: 8760 hours /3107 flares = **2.8 hours.**
M-class flares: 8760 / 311 = **28 hours = 1 day**
X-class flares: 8760 / 20 = **438 hours = 18 days**

B) 10 pFU: 8760/8 = **1,095 hours = 1.5 months**
100 pFU: 8760/5 = **1,752 hours = 2.5 months**
1000 pFU: 8760/2 = **4,380 hours = 6 months**
10000 pFU: 8760/1 = **8,760 hours = 1 year**

C) Halo CME: 8760 / 41 = **214 hours or 9 days**.

Problem 2 - Assuming that Halo CMEs and X-class flares occur randomly over the year, what is the probability that during 2001 you will see both a Halo CME and an X-class flare on the same day?

Answer: During this year there were 20 X-class flares and 41 Halo CMEs. Each day the probability is 20/365 = 1/18 that an X-class flare will occur, and 41/365 = 1/9 that a Halo CME will occur. The probability is then P(Halo) x P(Xflare) = 1/18 x 1/9 = **P(both) = 1/162** = 0.006 that both will happen on the same day.

Additional Resources about Radiation

NASA Radiation Effects and Analysis - a technical resource about how radiation in space affects electrical devices

http://radhome.gsfc.nasa.gov/

NASA Space Radiation and Analysis Group - At Johnson Spaceflight Center, this resource covers the effects of radiation on astronauts. They have an excellent Guide to space radiation and some FAQs answered.

http://srag-nt.jsc.nasa.gov/

NASA Human Adaptation and Countermeasures - Additional NASA resource describing programs to help protect astronauts from radiation exposure in space, and studies of the consequences.

http://hacd.jsc.nasa.gov/projects/space_radiation.cfm

The NASA-Brookhaven Radiation Lab - This laboratory studies radiation effects to organic tissues and electrical devices using a particle accelerator at the Brookhaven National Radiation Laboratory in New York.

http://www.bnl.gov/medical/NASA/LTSF.asp

NASA Radiation Physics Office - This resource has a number of links and documents that explain the many radiation hazards in working in the space environment

http://radhome.gsfc.nasa.gov/radhome/rpo.htm

The Human Impacts of Space Weather - An extensive resource covering all aspects of space weather hazards including radiation. Written by a NASA Astronomer Dr. Sten Odenwald, the website also include extensive historical documents about previous solar storms, and radiation hazards to astronauts.

http://www.solarstorms.org/

A note from the Author,

Radiation is one of those topics that have been a source of public concern ever since the first 'atom bomb' was detonated. Before the Atmospheric Test Ban Treaty was signed in the mid 1960's, hundreds of nuclear bombs were detonated above ground, spewing forth kilotons of radioactive dust and debris that took up temporary residence in the atmosphere. Cows ate grasses and produced milk with high levels of strontium-90, while other isotopes of iodine and potassium also made their way into our food, at least for a decade or two. Then came the development of nuclear power plants, the accidents at Three Mile Island and Chernobyl. Non-nuclear sources of radiation also became a growing public concern, including high-voltage power lines and cell phones. So, it is not surprising that the Public, through numerous media reports, accidents, and scientific studies, have learned to be wary of 'radiation' and to consider it not only bad in all forms, but something that our Government should strictly regulate.

The problem is that radiation exposure is a biologically complex subject that cannot be described in a few sound-bites or slogans. Like it or not, we exist in a sea of radiation that we can do nothing about. Cosmic rays, natural radioactivity in our soils and clays, and radon gas in our basements, make up 80% of our natural background dose, and cannot be eliminated. Even the bananas we eat give us a measurable dosage of radioactivity.

Because radiation exposure is so important to NASA, the health of its astronauts, and operation of sensitive equipment, this book is dedicated to de-mystifying 'radiation' through concrete mathematical exercises. I hope that you and your students gain a better appreciation of this subject, and learn to think about it with increased clarity!

Sten Odenwald

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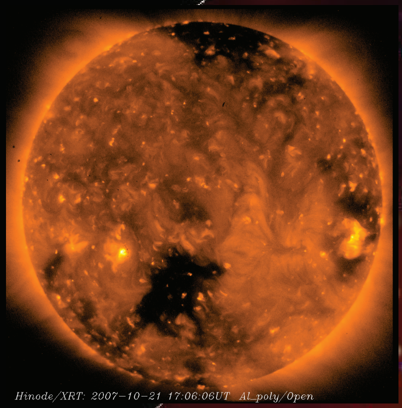

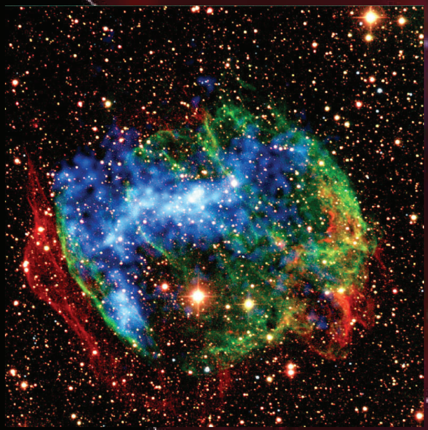

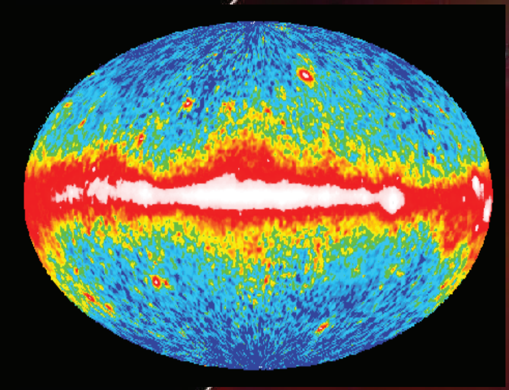

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