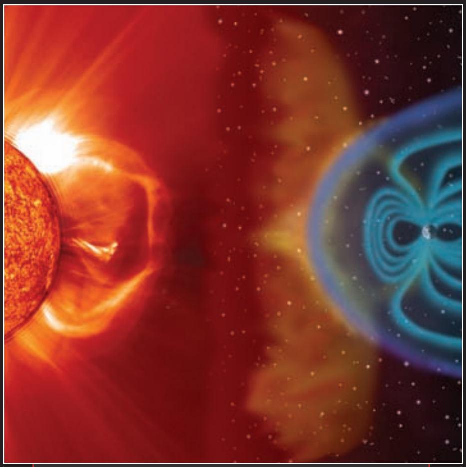
National Aeronautics and Space Administration

Space Faring
The Radiation Challenge

An Interdisciplinary Guide on Radiation and Human Space Flight



Middle School Educator Guide

Educational Product	
Educators	Grades 6–8

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Radiation

What Is Radiation?

Radiation is a form of energy that is emitted or transmitted in the form of rays, electromagnetic waves, and/or particles. In some cases, radiation can be seen (visible light) or felt (infrared radiation), while other forms like x-rays and gamma rays are not visible and can only be observed directly or indirectly with special equipment. Although radiation can have negative effects both on biological and mechanical systems, it can also be carefully used to learn more about each of those systems.

The motion of electrically charged particles produces electromagnetic waves. These waves are also called "electromagnetic radiation" because they radiate from the electrically charged particles. They travel through empty space as well as through air and other substances. Scientists have observed that electromagnetic radiation has a dual "personality." Besides acting like waves, it acts like a stream of particles (called photons) that has no mass. The photons with the highest energy correspond to the shortest wavelengths and vice versa. The full range of wavelengths (and photon energies) is called the electromagnetic spectrum (shown in figure 3). The shorter the wavelength, the more energetic the radiation and the greater the potential for biological harm.

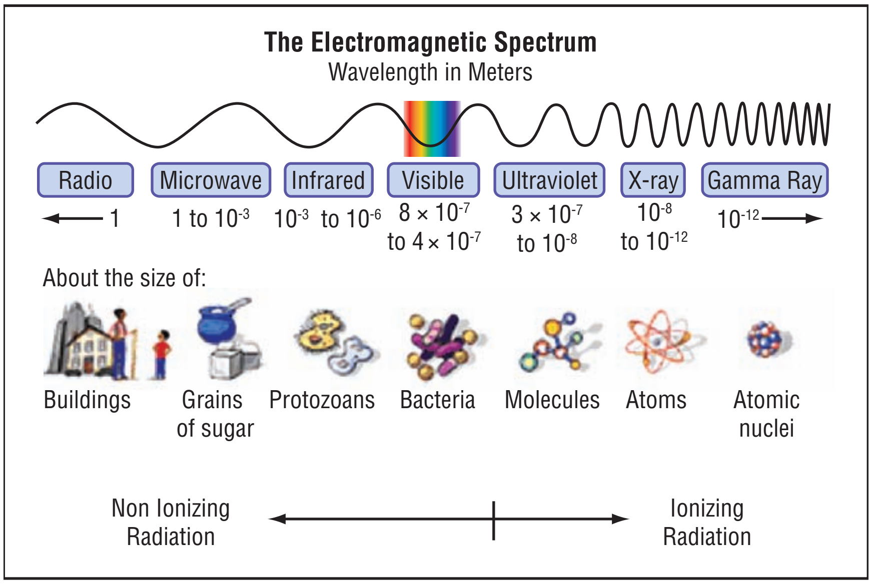


Figure 3: The Electromagnetic Spectrum

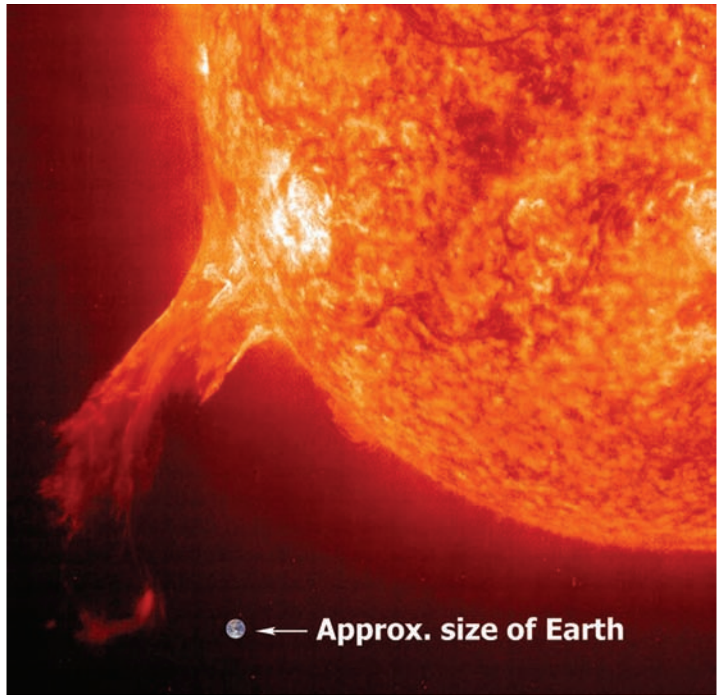
On Earth we are protected from much of the electromagnetic radiation that comes from space by Earth's atmosphere and magnetic field. Most radiation is unable to reach the surface of the Earth except at limited wavelengths, such as the visible spectrum, radio waves, some ultraviolet wavelengths, and some high-energy ionizing radiation. As we rise through the atmosphere, climb a high mountain, take a plane flight, or go to the ISS or to the Moon, we rapidly lose the protection of the atmosphere.

Where Does Radiation Come From?

In our daily lives we are exposed to electromagnetic radiation through the use of microwaves, cell phones, and diagnostic medical applications such as x-rays. In addition to human-created technologies that emit electromagnetic radiation such as radio transmitters, light bulbs, heaters, and gamma ray sterilizers (tools that kill microbes in fresh or packaged food), there are many naturally occurring sources of electromagnetic and ionizing radiation. These include radioactive elements in the Earth's crust, radiation trapped in the Earth's magnetic field, stars, and other astrophysical objects like quasars or galactic centers.

Earth's biggest source of radiation is the Sun. The Sun emits all wavelengths in the electromagnetic spectrum. The majority is in the form of visible, infrared, and ultraviolet radiation (UV). Occasionally, giant explosions called solar flares and coronal mass ejections (CME) occur on the surface of the Sun and release massive amounts of energy out into space in the form of x-rays, gamma

Figure 4: Erupting CME from the surface of the Sun.



rays, and streams of protons and electrons called solar particle events (SPE).[5] A robotic spacecraft called the Solar and Heliospheric Observatory (SOHO) captured an erupting CME from the surface of the Sun in the image in figure 4[6]. Note the Earth inset at the approximate scale of the image. These CME can have serious consequences on astronauts and their equipment, even at locations that are far from the Sun.

What Are the Different Kinds of Radiation?

Radiation can be either non-ionizing (low energy) or ionizing (high energy). Ionizing radiation consists of particles or photons that have enough energy to ionize an atom or molecule by completely removing an electron from its orbit, thus creating a more positively charged atom. Less energetic non-ionizing radiation does not have enough energy to remove electrons from the material it traverses. Examples of ionizing radiation include alpha particles (a helium atom nucleus moving at very high speeds), beta particles (a high-speed electron or positron), gamma rays, x-rays, and galactic cosmic radiation (GCR). Examples of non-ionizing radiation include radio frequencies, microwaves, infrared, visible light, and ultraviolet light. While many forms of non-ionizing and ionizing radiation have become essential to our everyday life, each kind of radiation can cause damage to living and non-living objects, and precautions are required to prevent unnecessary risks.

5 http://solarscience.msfc.nasa.gov/CMEs.shtml
6 http://www.nasa.gov/vision/universe/solarsystem/perfect_space_storm.html

Why Is Ionizing Radiation More Dangerous Than Non-Ionizing Radiation?

While non-ionizing radiation is damaging, it can easily be shielded out of an environment as is done for UV radiation. Ionizing radiation, however, is much more difficult to avoid. Ionizing radiation has the ability to move through substances and alter them as it passes through. When this happens, it ionizes (changes the charge of) the atoms in the surrounding material with which it interacts. Ionizing radiation is like an atomic-scale cannonball that blasts through material, leaving significant damage behind. More damage can also be created by secondary particles that are propelled into motion by the primary radiation particle. The particles associated with ionizing radiation are categorized into three main groups relating to the source of the radiation: trapped radiation belt particles (Van Allen Belts), cosmic rays, and solar flare particles.[7]

What Is Galactic Cosmic Radiation?

Galactic Cosmic Radiation, or GCR, comes from outside the solar system but primarily from within our Milky Way galaxy. In general, GCR is composed of the nuclei of atoms that have had their surrounding electrons stripped away and are traveling at nearly the speed of light. Another way to think of GCR would be to imagine the nucleus of any element on the periodic table from hydrogen to uranium. Now imagine that same nucleus moving at an incredibly high speed. The high-speed nucleus you are imagining is GCR. These particles were probably accelerated within the last few million years by magnetic fields of supernova remnants (but not the supernova explosion itself). The giant expanding clouds of gas and magnetic fields that remain after a supernova can last for thousands of years.[8] During that time, cosmic rays were probably accelerated inside them. The action of the particles bouncing back and forth in the magnetic field of the supernova remnant randomly causes some of the particles to gain energy and become cosmic rays.[9] Eventually they build up enough speed that the remnant can no longer contain them and they escape into the galaxy. As they travel through the very thin gas of interstellar space, some of the GCR interacts with the gas and emits gamma rays. Detection of that reaction is how we know that GCR passes through the Milky Way and other galaxies.

The GCR permeates interplanetary space and is comprised of roughly 85% hydrogen (protons), 14% helium, and about 1% high-energy and highly charged ions called HZE particles. An HZE is a heavy ion having an atomic number greater than that of helium and having high kinetic energy. Examples of HZE particles include carbon, iron, or nickel nuclei (heavy ions). Though the HZE particles are less abundant, they possess significantly higher ionizing power, greater penetration power, and a greater potential for radiation-induced damage.[10] GCR is extremely damaging to materials and biology. In general, we are largely shielded from GCR on Earth because of our planet's atmosphere and magnetic field, whereas the Moon is not shielded from GCR because it lacks a global magnetic field and atmosphere.

In summary, GCR are heavy, high-energy ions of elements that have had all their electrons stripped away as they journeyed through the galaxy at nearly the speed of light. They can cause the ionization of atoms as they pass through matter and can pass practically unimpeded through a typical spacecraft or the skin of an astronaut. The GCR are a dominant source of radiation that must be dealt with aboard current spacecraft and future space missions within our solar system. Because these particles are affected by the Sun's magnetic field, their average intensity is highest during the period of minimum sunspots when the Sun's magnetic field is weakest and less able to deflect them. Also, because GCR are difficult to shield against and occur on each space mission, they are often more hazardous than occasional solar particle events.[11] Figure 5 shows GCR falling onto the surface of Mars. GCR appear as faint white dots, whereas stars appear as white streaks.

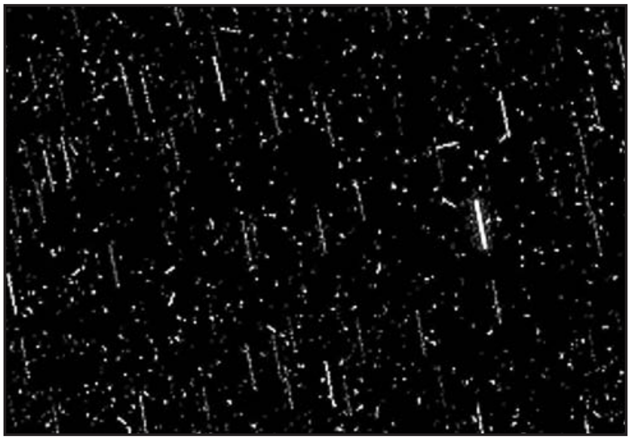


Figure 5: GCR appear as dots in this image. Image credit: NASA.

7 http://see.msfc.nasa.gov/ire/iretech.htm
8 http://helios.gsfc.nasa.gov/gcr.html
9 http://imagine.gsfc.nasa.gov/docs/science/know_l1/cosmic_rays.html
10 http://hrp.jsc.nasa.gov/?viewFile=program/srp
11 www.spaceflight.nasa.gov/spacenews/factsheets/pdfs/radiation.pdf

Are We Protected from Space Radiation on Earth?

Yes, but not entirely. Life on Earth is protected from the full impact of solar and cosmic radiation by the magnetic fields that surround the Earth and by the Earth's atmosphere. The Earth also has radiation belts caused by its magnetic field. The inner radiation belt or Van Allen Belt consists of ionizing radiation in the form of very energetic protons—by-products of collisions between GCR and atoms of Earth's atmosphere. The outer radiation belts contain ions and electrons of much lower energy. As we travel farther from Earth's protective shields we are exposed to the full radiation spectrum and its damaging effects.[12]

In addition to a protective atmosphere, we are also lucky that Earth has a magnetic field. It shields us from the full effects of the solar wind and GCR. Without this protection, Earth's biosphere might not exist as it does today, or would be at least limited to the subsurface. The small blue torus near the Earth in figure 6[13] is the approximate location of the Van Allen Belts, where high-energy radiation is trapped.

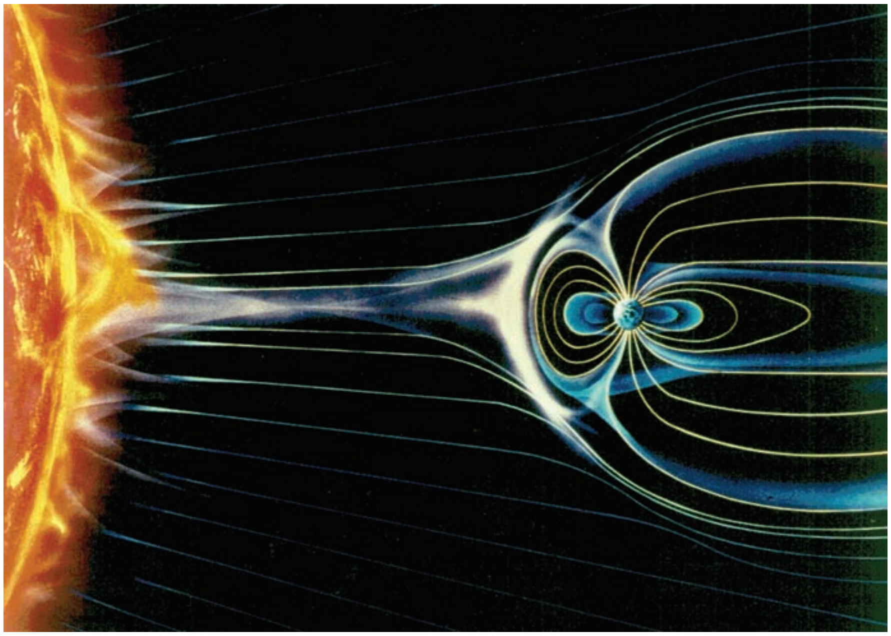


Figure 6: Van Allen Belts.
Image Credit: NASA.

12 http://www-istp.gsfc.nasa.gov/Education/Iradbelt.html
13 http://science.msfc.nasa.gov/ssl/pad/solar/images/sunearth_lg.gif

What Factors Determine the Amount of Radiation Astronauts Receive?

There are three main factors that determine the amount of radiation that astronauts receive. They include:[14]

- Altitude above the Earth – at higher altitudes the Earth's magnetic field is weaker, so there is less protection against ionizing particles, and spacecraft pass through the trapped radiation belts more often.
- Solar cycle – the Sun has an 11-year cycle, which culminates in a dramatic increase in the number and intensity of solar flares, especially during periods when there are numerous sunspots.
- Individual's susceptibility – researchers are still working to determine what makes one person more susceptible to the effects of space radiation than another person. This is an area of active investigation.

Does Space Weather Affect Astronauts?

Absolutely. Space weather is closely related to solar activity and this is important for astronauts traveling through space. Scientists have discovered that over an 11-year cycle the number of sunspots increase and decrease as shown in figure 7.[15] Interestingly, the Sun is slightly brighter when there are many sunspots. During one of these periods, the Sun is more actively producing SPE and CME so the amount of radiation in the solar system is slightly increased. The number of CMEs varies with the solar cycle, going from about one per day at solar minimum, up to two or three per day at solar maximum. Although scientists can predict that the Sun can produce more SPE and CME during this period, they are unable to determine specifically when SPE and CME will occur.

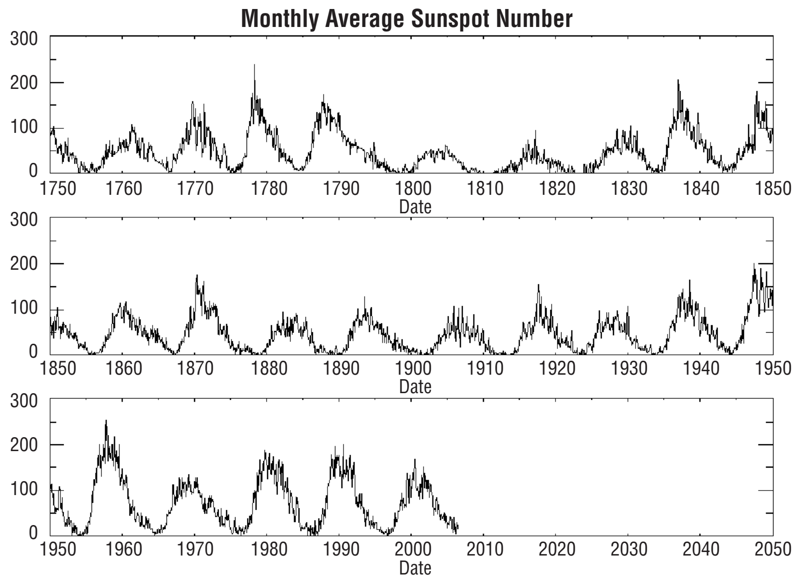


Figure 7: The sunspot cycle of the Sun.
Image credit: NASA.

14 www.spaceflight.nasa.gov/spacenews/factsheets/pdfs/radiation.pdf
15 http://solarscience.msfc.nasa.gov/images/zurich.gif

Because the levels of protection vary, the radiation environments vary between planets and moons, even at different places on the surface of individual planets. The ISS has well-shielded areas. In addition, astronauts and the ISS itself are largely protected by the Earth's magnetic field because it is in low Earth orbit. In contrast, during a deep space journey to the Moon (240,000 miles or 385,000 kilometers away) or Mars (35,000,000 miles or 56,300,000 kilometers away at closest approach), astronauts and their vehicles will venture far outside of the 30,000-mile radius of the Earth's protective magnetic shield. For any future long-duration deep-space exploration, radiation levels will be so high that specially designed storm shelters will be needed to protect astronauts from receiving deadly doses of radiation during high SPE/CME periods. For safe operations on the Moon or when traveling to Mars, a coordinated system of satellites will be needed to monitor space weather to help warn astronauts when it is necessary to go into their shelters.[16] This is because, although increases and decreases in overall solar activity can be fairly well predicted over an 11-year cycle, there are unexpected short-term events like solar flares, SPE, and CME that cannot be predicted, which would put a crew in great danger.

How Is Radiation Measured?

There are several properties of radiation that must be considered when measuring or quantifying radiation. These include the magnitude of radioactivity of the source, the energy of the radiation itself, the amount of radiation in the environment, and the amount of radiation energy that is absorbed. Collectively, these properties determine the nature of the radiation itself. It is very important to understand that equal doses of different kinds of radiation are not equally damaging. To account for the difference, radiation dose is expressed as "dose equivalent." Table 1 summarizes each parameter:

Table 1: Dose equivalent chart.

Parameter	Radioactivity	Absorbed Dose	Dose Equivalent*	Exposure (for x-rays and gamma rays only)	Energy
Definition	Rate of radiation emission (transformation or disintegration) from a radioactive substance	Energy imparted by radiation per unit mass onto an absorbing material	Expression of dose in terms of its biological effect	Quantity that expresses the ability of radiation to ionize air and thereby create electric charges that can be collected and measured	The capacity to do work
Common Units Measurement Label	curie (Ci) 1 Ci = 37 GigaBq (this is a large amount)	rad 1 rad = 100 ergs/g	rem	roentgen (R)	joule (J)
International System of Units (SI) Measurement Label	becquerel (Bq) 1 Bq = 1 event of radiation emission per second (this is a very small amount)	Gray (Gy) 1 Gy = 100 rad	sievert (Sv) 1 Sv = 100 rem (this is a large dose) 1 Gy air dose equivalent = 0.7 Sv 1 R ≈ 10 mSv of tissue dose	coulomb/kilogram (C/kg) 1 R = 2.58×10^{-4} C/kg air	electronvolts (eV)

*DE = Absorbed Dose × Quality Factor (Q), where Q depends on the type of radiation
Q = 1 for gamma, x-ray, or beta radiation; Q = 20 for alpha radiation

When measuring radiation energy another consideration is that equal doses of all types of ionizing radiation do not produce the same harmful biological effects. In particular, alpha particles (the nuclei of the helium atom) exert more damage than do beta particles, gamma rays, and x-rays for a given absorbed dose depositing their energy thousands of times more effectively. While lower energy electrons can pass through the spacing between DNA strands without interacting, some high-energy heavy ions produce an ionization trail so intense that it can kill nearly every cell it traverses (see the radiation damage in the living organisms section for more detail).

16 http://marsprogram.jpl.nasa.gov/spotlight/odyssey-mission-success.html

To account for the difference in harmful effects produced by different types of ionizing radiation, radiation dose is expressed as dose equivalent. The unit of dose equivalent is the sievert (Sv). The dose in Sv is equal to "absorbed dose" multiplied by a "radiation weighting factor" that was previously known as the Quality Factor (Q). Historically, x-rays have been used as the standard reference radiation against which all other types of radiation have been compared so the weighting factor for x-rays and gamma rays is 1. Since alpha particles cause 20 times the damage of a similar dose of x-rays or gamma rays, they have a Q of 20.

Some books use the rem to measure dose equivalent. One Sv, or 100 rem of radiation, is presumed, for the purpose of radiation protection, to have the same biological consequences as 1 Gray (Gy) of x-rays. Although there are exceptions, in general when radiation energy is transferred, the deposited energy (absorbed dose) is closely related to the energy lost by the incident particles.[17] The energy imparted is expressed in the unit Gy, which is equivalent to one joule of radiation energy absorbed per kilogram of organ or tissue weight. However, it should be noted that an older unit—the rad—is still frequently used to express absorbed dose; one Gy is equal to 100 rad.

Are There Radiation Exposure Limits?

Yes. The specific organ and career exposure limits are determined by one's age and gender. The typical average dose for a person is about 360 mrems per year, or 3.6 mSv, which is a small dose. However, International Standards allow exposure to as much as 5,000 mrems (50 mSv) a year for those who work with and around radioactive material. For spaceflight, the limit is higher. The NASA limit for radiation exposure in low-Earth orbit is 50 mSv/year, or 50 rem/year. Note that the values are lower for younger astronauts as seen in table 2. Since it is presumed that, although they may live longer than older astronauts, exposure to larger amounts of radiation early in their careers could present greater health risks during old age.

Table 2: Exposure limits for NASA astronauts.

Career Exposure Limits for NASA Astronauts by Age and Gender*				
Age (years)	25	35	45	55
Male	1,500 mSv	2,500 mSv	3,250 mSv	4,000 mSv
Female	1,000 mSv	1,750 mSv	2,500 mSv	3,000 mSv

* Please visit the website for more information on radiation exposure limits. [18]

The career depth equivalent dose limit is based upon a maximum 3% lifetime excess risk of cancer mortality. The total equivalent dose yielding this risk depends on gender and age at the start of radiation exposure. Assume that a younger person can be exposed to less radiation because they have more life to live, and therefore a longer chance to develop subsequent health problems. Table 3 compares the specific exposure limits between the general public and astronauts. Astronauts who spend three months in the ISS will be subjected to over three times the maximum recommended dosage of radiation for one year.

17 For example, high-energy electrons produced by charged particles traversing a cell may escape, to deposit their energy in other locations, outside the cell. At low dose rates, only one or a few particles are likely to traverse a cell. The energy deposited in the cell is less than the energy lost by the particles. However, when a large number of particles are present, then electrons generated outside the cell may compensate for those that are lost. Thus, the concept of absorbed dose incorporates many assumptions and approximations.

18 http://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm

Activity I: Radiation Exposure on Earth

In Activity I, students will use worksheets to determine their average annual radiation dose here on Earth.

Background

Radiation is a form of energy that is emitted or transmitted in the form of rays, electromagnetic waves, and/or particles. In some cases, radiation can be seen (visible light) or felt (infrared radiation), while other forms like x-rays and gamma rays are not visible and can only be observed directly or indirectly with special equipment. Although radiation can have negative effects both on biological and mechanical systems, it can also be carefully used to learn more about each of those systems.

On Earth we are protected from much of the electromagnetic radiation that comes from space by Earth's atmosphere and magnetic field. Most radiation is unable to reach the surface of the Earth except at limited wavelengths, such as the visible spectrum, radio waves, some ultraviolet wavelengths, and some high-energy ionizing radiation. As we rise through the atmosphere, climb a high mountain, take a plane flight, or go to the International Space Station (ISS) or to the Moon, we rapidly lose the protection of the atmosphere and magnetic field.

Please see the introduction for more background about radiation.

Objectives:

By the end of this lesson, the students will be able to:

- Explain that radiation exposure on Earth is determined mainly by where people live, how people live (lifestyle), and by the medical procedures people have experienced.
- Determine their average annual radiation dose here on Earth.
- Describe some medical procedures that increase their radiation exposure.
- Explain the difference between acute and chronic radiation exposure.
- Compare their radiation exposure to an astronaut's radiation exposure.

Research Question:

How does your radiation exposure compare to an astronaut's radiation exposure, and why are they different?

Discussion Questions:

Regarding a human-tended lunar outpost, have students discuss in detail how and why radiation might affect the total duration astronauts can stay on the Moon. Other possible topics for discussion include:

- What are the different kinds of radiation?
- What units are used to describe radiation exposure?
- What is your annual radiation exposure?
- How does your radiation exposure compare to an Apollo 14 astronaut (use chart)?
- Are you exposed to radiation when watching TV?
- How does your altitude (height above sea level) affect your radiation exposure?
- What are some examples of medical procedures that are high in radiation?
- Does where you live on the Earth affect your radiation exposure?
- Does the Earth give off radiation?
- How can you reduce the amount of radiation you are exposed to?
- Why is radiation exposure more for ISS astronauts than for Space Shuttle astronauts?
- What kind of health effects due to radiation might Moon and Mars explorers experience?

Chart I. Spaceflight Radiation Examples	
Human Spaceflight Mission Type	**Radiation Dose**
Space Shuttle Mission 41-C (8-day mission orbiting the Earth at 460 km)	5.59 mSv
Apollo 14 (9-day mission to the Moon)	11.4 mSv
Skylab 4 (87-day mission orbiting the Earth at 473 km)	178 mSv
International Space Station (ISS) Mission (up to 6 months orbiting Earth at 353 km)	160 mSv
Estimated Mars mission (3 years)	1200 mSv

Note: units of exposure on this chart are in milliSieverts (mSv). 1 Sv = 1000 mSv.

Chart II. Examples of Health Effects from Acute Radiation Exposure		
Exposure (mSv)	**Acute Health Effects***	**Time to Onset (without treatment)**
Less than 100	No detectable health effects	
Above 100	Cell and chromosomal (DNA) damage	hours
Above 1,000	Nausea, vomiting, diarrhea: prodromic syndrome	1 to 2 days
Above 1,500	Damage to blood-forming organs: hematopoietic syndrome; possible death	≈1 month
3,000	50% death from hematopoietic syndrome	in 30 to 60 days
10,000	Destruction of intestinal lining	
	Internal bleeding	
	Death	1-2 weeks
20,000	Damage to central nervous system	
	Loss of consciousness	minutes
	Death	hours to days

Note: units of exposure on this chart are in Sieverts (Sv). 1 Sv = 1,000 mSv.
* The acute effects in this table are cumulative. For example, a dose that causes damage to bone marrow will produce changes in blood chemistry and be accompanied by nausea. At a certain threshold every individual will experience these kinds of effects, which include nausea, skin reddening, sterility, and cataract formation.

Chart III. Comparison of Radiation Doses	
Description	**Exposure (mSv)**
A single dental, arm, hand, foot, or leg x-ray	0.01
A single chest x-ray	0.06
A single skull/neck x-ray	0.2
A single pelvis/hip x-ray	0.65
A single CAT scan of body	1.1
A single upper GI x-ray	2.45
One year of normal radiation on Earth (approximate)	3.0
8 days on the Space Shuttle	5.59
9 days on the Moon	11.4
6 months on the International Space Station	160
Lowest dose received during 1945 Hiroshima bomb	200
Estimated dose for a 3-year round trip for a Mars Mission	1,200

Note: The items in Chart III are plotted in Graph 1 (see next page).

Radiation Exposure on Earth

Name: ______________________________ **Date:** ____________________

Directions: Estimate your annual radiation dose by adding together the amount of radiation you are exposed to from common sources of radiation. Place the value from the "Common Sources of Radiation" column (middle column) that corresponds to your situation in the "Annual Dose" column (right column). All values are in milliSieverts (mSv). Add all of the numbers in the right column to determine your total estimated annual radiation dose. Answer the discussion questions.

Factors	Common Sources of Radiation		Annual Dose
Where You Live	**Cosmic Radiation (from outer space)** Exposure depends on your elevation (how much atmosphere is above you to block radiation).		________mSv
	Elevation (average cities' data from the United States Geological Survey website: http://www.usgs.gov)	**Value (mSv)**	
	Sea level (New York, Philadelphia, Houston, Baltimore, Boston, New Orleans, Jacksonville, Seattle)	0.26	
	1-1,000 feet (Chicago, Detroit, San Diego, Dallas, Minneapolis, St. Louis, Indianapolis, San Francisco, Memphis, Washington, DC, Milwaukee, Cleveland, Columbus, Atlanta)	0.28	
	1,001-2,000 feet (Phoenix, Pittsburgh, San Jose, Oklahoma City)	0.31	
	2,001-3,000 feet (Las Vegas, Los Angeles, Honolulu, Tucson)	0.35	
	3,001-4,000 feet (El Paso)	0.41	
	4,001-5,000 feet (Salt Lake City)	0.47	
	5,001-6,000 feet (Denver, Albuquerque)	0.52	
	6,001-7,000 feet	0.66	
	7,001-8,000 feet	0.79	
	8,001-9,000 feet	0.96	
	Terrestrial Radiation (from the ground) • If you live in a state that borders the Gulf of Mexico or Atlantic Ocean, add 0.16 mSv. • If you live in the Colorado Plateau area (around Denver), add 0.63 mSv. • If you live anywhere else in the continental U.S., add 0.30 mSv.		________mSv
	House Construction • If you live in a stone, adobe, brick, or concrete building, add 0.07 mSv.		________mSv
	Power Plants • If you live within 50 miles of a nuclear power plant, add 0.0001 mSv. (For locations of nuclear power plants, visit the United States Nuclear Regulatory Commision website: http://www.nrc.gov/info-finer/reactor) • If you live within 50 miles of a coal-fired power plant, add 0.0003 mSv.		________mSv
Food **Water** **Air**	**Internal Radiation (average values)** • From food (most food has naturally occurring radioactive Carbon-14 and Potassium-40) and from water (radon dissolved in water). • From air (radon emanating from the ground).		______0.40 mSv ______2.00 mSv
Total	Add all the values for your annual radiation dose in the third column.		________mSv

Factors	Common Sources of Radiation		Annual Dose
Total (page 1)	Transfer the total from the previous page onto this line.		_________mSv
How You Live	**Add the following values if they apply to you:**		
	Live near a weapons test fallout site	0.01 mSv	_________mSv
	Jet plane travel	0.005 mSv per hour in the air (total for all flights in one year)	_________mSv
	If you have porcelain crowns or false teeth	0.0007 mSv per tooth/ crown (2 crowns = 0.0014 mSv)	_________mSv
	If you wear a luminous wrist-watch	0.0006 mSv	_________mSv
	If you watch TV	0.01 mSv	_________mSv
	If you use a computer screen	0.01 mSv	_________mSv
	If you have a smoke detector	0.00008 mSv	_________mSv
	If you use a gas camping lantern	0.002 mSv	_________mSv
	If you smoke	160.0 mSv	_________mSv
Medical Tests	**Medical diagnostic tests performed on you this year (per procedure)**		
	Extremity x-ray (arm, hand, foot, or leg)	0.01 mSv (if you had two x-rays, then = 0.02 mSv)	_________mSv
	Dental x-ray	0.01 mSv	_________mSv
	Chest x-ray	0.06 mSv	_________mSv
	Pelvis/hip x-ray	0.65 mSv	_________mSv
	Skull/neck x-ray	0.20 mSv	_________mSv
	Upper gastro-intestinal x-ray	2.45 mSv	_________mSv
	CAT scan (head and body)	1.1 mSv	_________mSv
	Nuclear medicine (e.g. thyroid scan)	0.14 mSv	_________mSv
Total Annual Dose	Add up all of the numbers in the third column of this page. This is your annual radiation dose on Earth.		_________mSv

Radiation Damage in Living Organisms

As we have discussed, space radiation can penetrate habitats, spacecraft, equipment, spacesuits, and even astronauts themselves. The interaction of ionizing radiation with living organisms can lead to harmful health consequences such as tissue damage, cancer, and cataracts in space and on Earth. The underlying cause of many of these effects is damage to deoxyribonucleic acid (DNA). The degree of biological damage caused by ionizing radiation depends on many factors such as radiation dose, dose rate, type of radiation, the part of the body exposed, age, and health. In this section, we will discuss the risks and symptoms of space radiation exposure including how and why this radiation causes damage, and how the body works to repair the damage. We will also discuss how scientists study the effects of radiation on living organisms, and why this research is important to NASA.

Why Is NASA Studying the Biological Effects of Radiation?

NASA wants to keep astronauts safe and healthy during long-duration space missions. To accomplish this challenging task, NASA has identified four significant health risks due to radiation that must be well understood to enable the development of effective countermeasures. The risks are described in the NASA Bioastronautics Critical Path Roadmap, and include carcinogenesis, acute and late central nervous system risks, chronic and degenerative tissue risks, and acute radiation risks.[23] NASA scientists are working to understand the molecular, cellular and tissue mechanisms of damage, which include DNA damage processing, oxidative damage, cell loss through apoptosis or necrosis, changes in the extra-cellular matrix, cytokine activation, inflammation, changes in plasticity, and micro-lesions (clusters of damaged cells along heavy ion tracks). Knowing this information will help researchers develop the appropriate countermeasures.

How Do Scientists Study Biological Change During Spaceflight?

Because the radiation environment in space is different than that on Earth, the biological responses are different. As a result, NASA scientists must develop space biology experiments that are designed to carefully study model organisms in space. In this scenario, the organism is sent into space and allowed to grow and develop. This part of the experiment is called the flight experiment. The same experiment is also repeated on the Earth, and this is called a ground control, an example of which is shown in figure 1. Careful analysis of both the flight experiment and ground controls are critical to understanding the biological changes that result from spaceflight.

Figure 1: NASA Ames researchers in the Drosophila lab.

Many studies are also carried out in ground-based research. Opportunities to fly experiments can be rare, and experiments must be well planned. Ground-based research allows a variety of parameters to be tested so that the investigator can decide which will be the best to focus on in a spaceflight experiment. For radiation studies, ground-based research can also help in identifying the specific biological responses for a particular radiation source. This is because on Earth, biological experiments can be carried out using a source that simulates just one kind of radiation, rather than the complex mix of radiation types that make up the space radiation environment. With a better understanding of biological responses to space radiation, we will be able to better design our countermeasures.

Using Non-Human Organisms to Understand Radiation Damage

To fully understand the biological response of radiation in humans, NASA scientists begin the process by studying model organisms. In general, biological systems are similar across many species; studying one animal can lead to deeper understandings of other

23 http://bioastroroadmap.nasa.gov/User/risk.jsp

animals, even humans. Some animals are easier to study than others, and those with short life cycles make it quicker to study multigenerational genetic effects. Another reason these organisms are commonly used is because scientists know a great deal about them. For most model organisms, their entire genome, physiological, and behavioral characteristics are well understood. Model organisms are small in size, so large numbers of them can be grown and studied in a small volume, which is very important for the confined environment aboard spacecraft. Having a large population to study also reduces the statistical variation and makes the research more accurate. Much of our understanding of life and human disease is because of scientists' work with model organisms. This is also true for what is known about the biological effects of space radiation. Examples of model organisms include bacteria, yeast, worms, plants, fruit flies, and many others. Fruit flies (fig.2), like humans, have reduced ability to learn when they are deprived of sleep. They can also sense the direction of gravity, and are affected by radiation. Moreover, they have many things in common with humans, including cellular processes, brain cell development, similar behaviors, and nearly identical disease genes. In fact, there is a great deal of similarity, or homology, between the DNA of these organisms and humans.

Figure 2: The fruit fly is a model organism.

Other organisms like ordinary baker's yeast (Saccharomyces cerevisiae) also contain genes for DNA repair that are very similar to human genes with the same function. Therefore we can use yeast as a model system to explore the effects of radiation on cells. Like human cells, most yeast cells effectively repair DNA damage caused by UV radiation. However, some yeast strains have mutations that prevent them from performing certain types of DNA repair. Because they cannot repair all the DNA damage, these cells usually die after exposure to UV radiation. In addition to sensitivity to UV radiation, yeast is also sensitive to space radiation. In a biological assessment of space radiation in low-Earth orbit, yeast inside special experiment hardware has been shown to have a decreased rate of survival following exposure to beta particles (electrons) and low-energy protons.[24] Other findings suggest there are highly coordinated gene expression responses to gamma radiation. This knowledge is especially important when designing countermeasures for astronauts during long-term lunar surface operations or microgravity spacewalks.

Plants are also commonly used in radiation studies. It has been shown that plant growth is inhibited by radiation. Like mammals, the embryo of a plant is very sensitive to radiation damage as compared to the adult. The rate of seed germination is reduced, and the rate of growth is slowed.[25] Excessive UV radiation will lead to an inhibition of plant growth processes in general. Such alterations in primary productivity (photosynthesis) can change entire ecosystems in the oceans, on land, and even in bioregenerative life support systems that would be aboard future spacecraft. Thus, NASA scientists must understand how plants respond to radiation if future space explorers depend upon the plants for nutrient cycling and food. Experiments involving plants in space, like the Biomass Production System, have been a favorite of astronauts during long-duration stays onboard the International Space Station (fig.3).[26]

Figure 3: NASA scientists are looking for better ways to grow plants both on Earth and in space.

24 http://mediaarchive.ksc.nasa.gov/detail.cfm?mediaid=5186
http://www.nasa.gov/images/content/58483main_Peggy_Whitson_Plants.jpg

25 www.esd.ornl.gov/programs/ecorisk/documents/tm13141.pdf

26 http://liftoff.msfc.nasa.gov/news/2003/news-plants.asp

What Are the Risks and Symptoms of Radiation Exposure for Humans?

It is important to note that the biological effects of acute and chronic radiation exposure vary with the dose. An average background radiation dose received by an average person can be approximately 3 mSv/year (including radon) without causing detectable harm while an exposure of 1 Sv/hour can result in radiation poisoning (nausea, vomiting). Figure 4 shows causes of radiation exposure to the average population. A person exposed to 100 mSv has a roughly 1 in 200 chance of developing cancer later in life, while a 1,000 mSv dose will cause cancer in about 1 in 20 people. Receiving 3,000 to 5,000 mSv during a short period of time (minutes) results in death in 50% of the cases. A person that experiences a massive 10,000 mSv dose will risk death in a matter of just a few days or weeks. Both acute and chronic exposure to such large doses can cause bleeding and inflammation due to lowered platelet counts. Suppressed immune system function and infections are possible due to lowered white blood cell counts. Reduced fertility or permanent sterility could also result. In addition to causing damage at the tissue, organ, and whole organism level, radiation has the ability to destroy molecules like DNA.

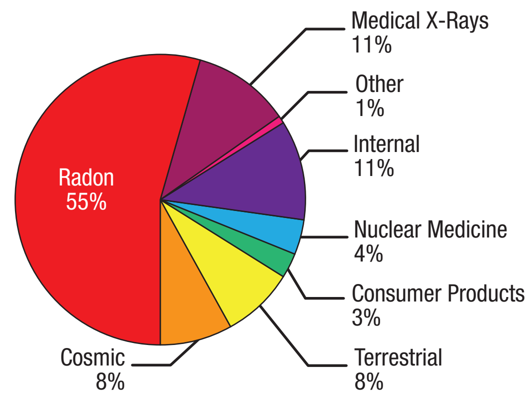


Figure 4: Radioactive radon gas produced from the breakdown of uranium in the Earth's crust accounts for over half of the radiation exposure to the general public. Image Credit: University of Illinois Extension.

What Is DNA?

DNA is the blueprint of life stored in the cells of every organism. DNA contains the code for all the information required for the synthesis of proteins, cell reproduction, and for organization of the tissues and organs. The information in the DNA is arranged in sections called genes. Gene codes are read by the cell's manufacturing system to make proteins. Proteins are the building blocks for biological structures and for the functional machinery of the body. Therefore it is vital to our health for the structure of DNA to remain intact.

What Is the Structure of DNA?

A DNA molecule (shown in fig. 5) has the shape of a double helix ladder that is only ≈2 nm wide. DNA is made of individual units called nucleotides. The information in DNA is coded in paired pyrimidine and purine nucleotides along an incredibly long molecule. A nucleotide contains three different types of molecules: a phosphate, a ribose sugar, and a base. The backbone of the helix is made of alternating phosphate and ribose sugar molecules. The rungs of the ladder are base pairs. Each ribose of the backbone has a base attached, which pairs with a base that extends from the opposite backbone. There are four different types of bases in DNA: adenine, thymine, guanine, and cytosine. DNA is arranged into 23 chromosomes in human cells. If stretched out, the DNA of one chromosome, on average, would be about 5 cm. If all DNA in a cell were lined end to end, the molecule would reach about 3 m. If you took all the DNA in all the cells from one human and lined it end to end, it would reach from the Earth to the sun 70 times.

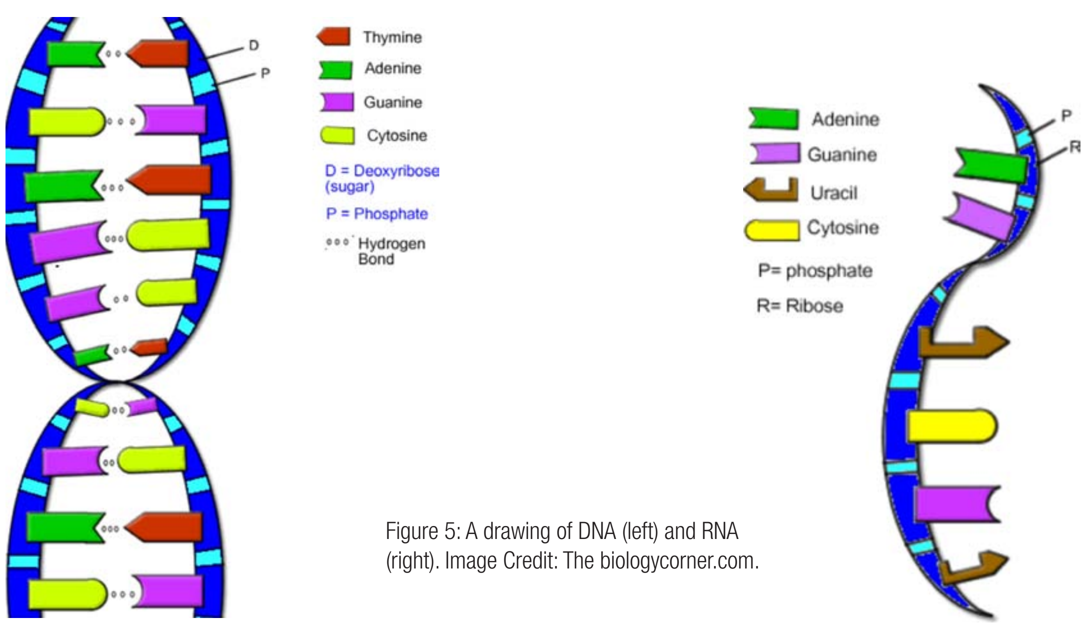


Figure 5: A drawing of DNA (left) and RNA (right). Image Credit: The biologycorner.com.

What Is DNA's Role in Protein Production?

DNA is the storage unit for the information used to make proteins. Before any protein manufacturing begins, the cell must transcribe DNA into another molecule. This other "messenger" molecule will carry only the code for the specific gene to a ribosome, which is the site of protein production. This messenger molecule is called ribonucleic acid (RNA). The ribosome reads the gene code of a messenger RNA and manufactures proteins by assembling long chains of amino acids together, one after another, in a process called translation. Each amino acid is coded for by a set of three nucleotides, or a codon, during translation of the RNA message, the RNA molecule sequence is read (translated) three consecutive nucleotides at a time. A protein typically consists of hundreds of amino acids that have been joined together. For example, imagine an RNA molecule that is 300 nucleotides long. That RNA molecule will be decoded by a ribosome, and the ribosome will construct a protein that is a chain of exactly 100 amino acids. A simplified chart summarizing protein production is shown in figure 6.

Figure 6: Protein production

What Kinds of DNA Damage Occur Due to Radiation?

DNA is normally a long, continuous molecule that stores tremendous amounts of information vital for a cell to function normally. When a DNA molecule is broken, the long chain of information is fragmented and the original message to produce specific proteins is lost. When DNA is broken on one strand of the double helix, it is called a single strand break (SSB). If both strands of the DNA double helix are severed within 10 to 20 base pairs of each other, the break is called a double strand break (DSB). Figure 7 shows two examples of DNA damage. Other forms of damage that can occur include the loss of a base, and base modification such as oxidation. In many cases, cells are able to fix such breaks with repair systems that are specialized for different types of damage. The damage sites that remain can cause assembly of proteins to be stopped or started prematurely. If DNA replication occurs before the repair system finds the damage, there is a chance that a modified nucleotide is misread as a different nucleotide. In addition, sometimes the repair systems misread a damaged nucleotide and replace it with the wrong nucleotide. The result in both cases is a point mutation. A point mutation is a single change in the nucleotide sequence of a gene. This can alter the amino acid code, so that the protein produced from the gene has a different composition. Depending on where in the protein this occurs, the altered protein sequence can have no affect, or it can alter the protein and protein function substantially. The result may cause cellular or tissue abnormality. In more extreme cases, the presence of DNA damage that cannot be properly repaired can trigger apoptosis, or cell suicide (see the next section for information about apoptosis and radiation countermeasures). The individual cell is sacrificed to prevent greater damage to the whole organism.

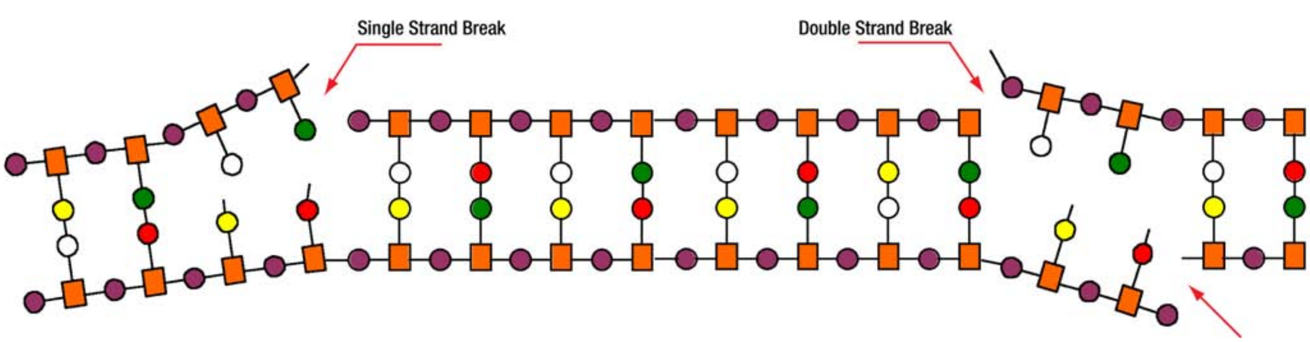


Figure 7: DNA model with two examples of DNA damage shown. The parallel linked sequences of orange squares (□) and purple circles (○) represent the phosphate(○)-deoxyribose sugar (□) strands, or backbone, of a DNA molecule. The pairs of circles linking the two strands represent nucleotide base pairs. In the single strand break, note that although some nucleotide base pairs have been separated, only one strand of the two DNA strands has been broken (indicated by red arrow). In the more severely damaged double strand break example, nucleotide pairs have been split apart and both strands of the DNA molecule are broken (indicated by red arrows).

In some cases, the effects of radiation-induced DNA damage may not be readily or immediately observable. While some damage may not be severe enough to cause death to a cell or organism, its effects can become apparent several generations later. Figure 8 is a diagram of a normal DNA molecule before and after being hit by ionizing radiation.[27]

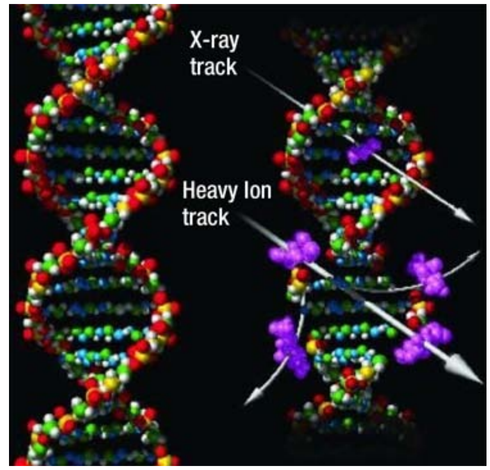


Figure 8: DNA before and after ionizing radiation.
Image Credit: NASA

Damage to DNA can be caused directly or indirectly. As the ion travels through material, it will lose some of its energy to the molecules around it. Cosmic radiation contains heavy ions, which are the nuclei of atoms with atomic weights ranging from 14 (carbon) to 55 (iron) or greater. This means that the atom is missing anywhere from 14 to 55 or more electrons. As this particle moves through material, it will pull electrons from any source it can find. This ionizes the molecules along the path of the heavy ion. Protons, alpha particles, or larger fragments can be forcibly separated from the DNA. In addition, when the heavy ion moves through water, the hydroxide ions in water (OH-) can be ionized, losing an electron, to give hydroxyl free radicals (·OH). Such species have a strong propensity to restore the electron pair by pulling a hydrogen atom, complete with a single unpaired electron, from carbon-hydrogen bonds in sugars. One excellent source for this within cells is DNA. Nucleotide modifications or removal, SSBs, DSBs, or any combination of these can occur along or near the track of a heavy ion.

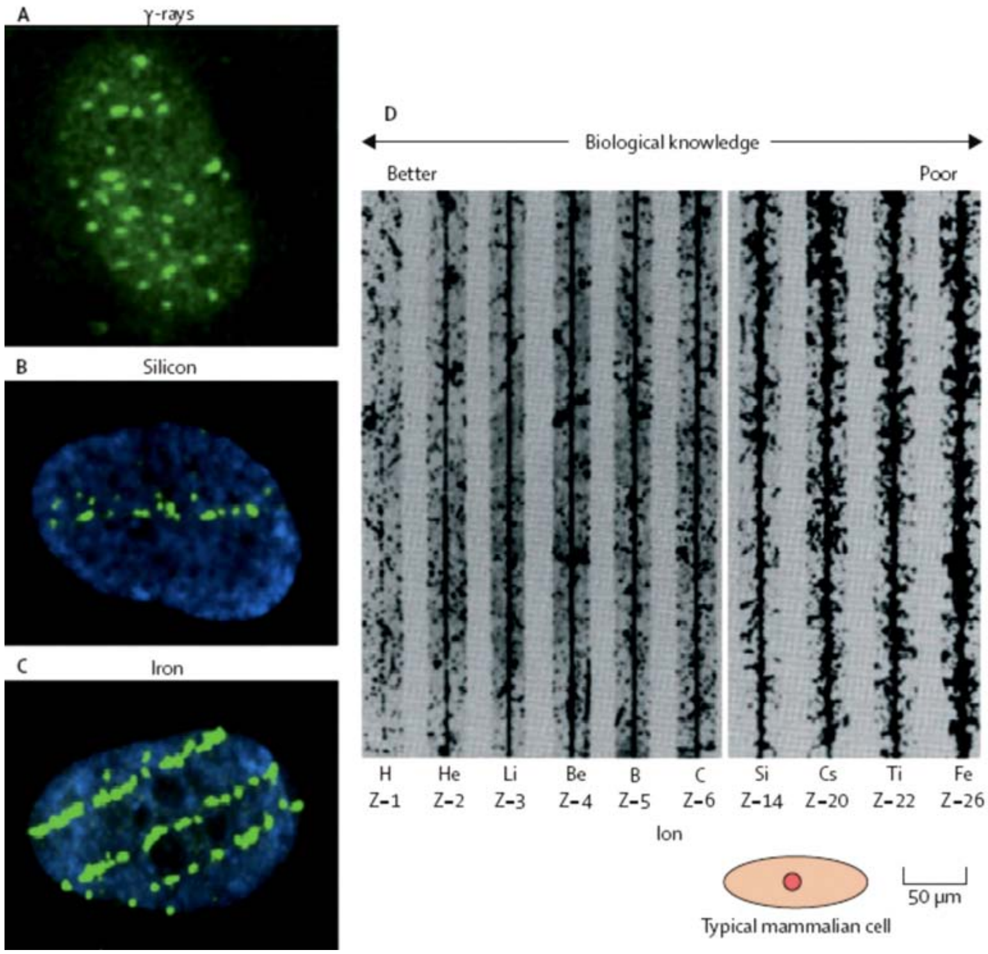
What Kind of Damage Can High Energy Ions Cause?

Because of their high ionization density, heavy ions and HZE particles (high energy ions, discussed in the radiation background material) can cause clusters of damage where many molecular bonds are broken along their trajectory through the tissue. The cell's ability to repair DNA damage becomes impaired as the severity of clustering increases. These particles can also create damage along a long column of cells in tissue. In other words, cells will be damaged in streaks along the path of an HZE particle. Since HZE particles are rare on Earth, the prediction of biological risks to humans in space must rely on fundamental knowledge gathered from biological and medical research.[28]

Figure 9: NASA Space Radiation Laboratory, at Brookhaven National Laboratory in Upton, New York.

Because spaceflight radiation biology experiments are extremely expensive and opportunities for flight are limited, NASA models spaceflight radiation exposure by studying organisms that have been exposed to radiation produced at special facilities here on Earth. Brookhaven National Labs (fig. 9)[29] and Lawrence Livermore National Laboratory[30] are two examples of facilities that have the ability to produce radiation that is similar to space radiation. This type of research greatly enhances our understanding of the biological response to space radiation, helps us to anticipate what may happen during future spaceflights, and develop countermeasures to help protect astronauts from radiation. For example, scientists have learned that mutations, chromosomal aberrations in plant seeds, development disturbances and malformations in small animal embryos, and even cell death in bacteria have resulted from the traverse of a single HZE particle. [31] Examples of cellular damage are shown in figure 10.

27 http://science.nasa.gov/headlines/y2004/17feb_radiation.htm
28 http://hrp.jsc.nasa.gov/?viewFile=program/srp
29 http://www.bnl.gov/medical/NASA/NSRL_description.asp
30 http://www.llnl.gov/
31 Acta Astronaut. 1994 Nov; 32(11):749-55.



This diagram[32] shows a comparison of radiation damage in three human cell nuclei (above left). The nuclei were exposed to (A) gamma rays, (B) silicon ions, and (C) iron ions. Following exposure, the cells were stained so the scientists could observe where DNA damage occurred. Every green spot is a DSB. Notice that the gamma ray (electromagnetic waves) exposure in (A) produced uniform damage, whereas cells exposed to high-energy heavy ions show DNA damage along the path traveled by the ion. In (B) there is one track and in (C) there are three tracks. The damage tracks of ions with differing masses are seen in (D). Note that heavier ions cause a wider path of destruction. Our understanding of biological damage caused by heavy ions is very limited. A cell has been drawn to scale for comparison purposes. Image Credit: crater.bu.edu.

What Are the Consequences of DNA Damage?

If radiation changes the number or order of nucleotides (mutation) within a DNA molecule, the information that is stored within the DNA is altered. This can cause significant problems in cell structures and even in their function. Even if a DNA molecule has had only one nucleotide deleted, that error could be perpetuated when translated into RNA. In other words, when the RNA is produced, it will be made as if that missing nucleotide had never existed in the first place. Interestingly, the ribosome will not know the difference, because the cell assembles the RNA based on what it reads in the DNA. As a result, the ribosome will assume that the information in the RNA is correct (although we know that the nucleotide order in the gene has been shifted by one nucleotide). Protein synthesis carries on, the triplet codons are read by the ribosome, and amino acids are gathered and assembled into a protein structure that the DNA had not coded for originally. In this example, a malformed protein will be constructed that could have significant negative consequences. In summary, when the genotype (genetic information) of a cell is changed, the phenotype (the outward observable expression of the genetic information) may also be changed. Radiation is an environmental stimuli that has the ability to influence whether or not a gene turns on and off, for example, some cancer genes.

32 Cucinotta, F., Lancet Oncol 2006; 7: 431–35.