

Space Radiation





Space Radiation

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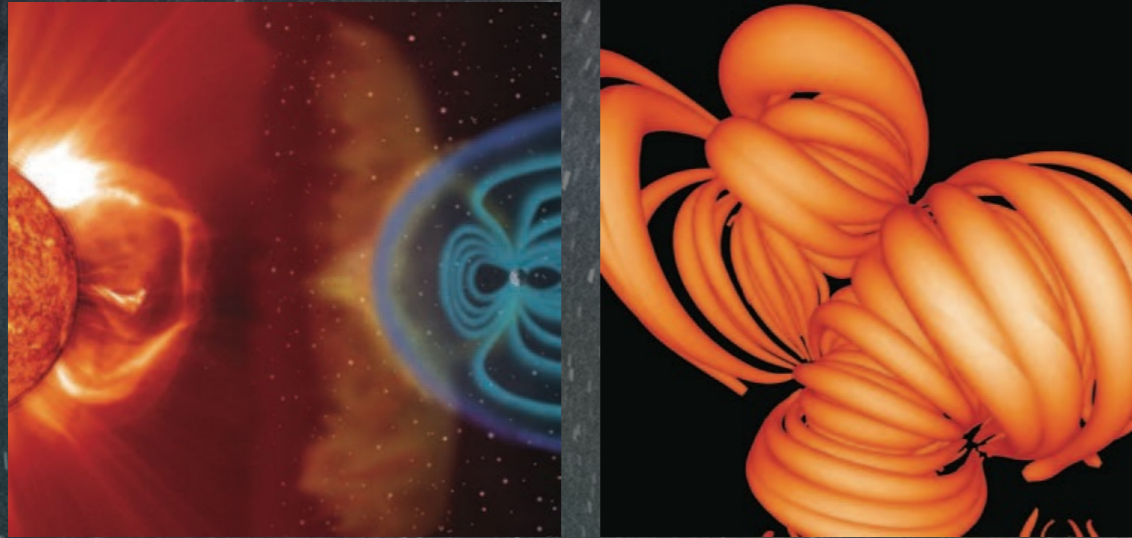
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Introduction



**NASA Human Research Program Engagement
and Communications**

Radiation iBook

Based on

Space Faring: The Radiation Challenge

An Interdisciplinary Guide on Radiation and Human
Space Flight

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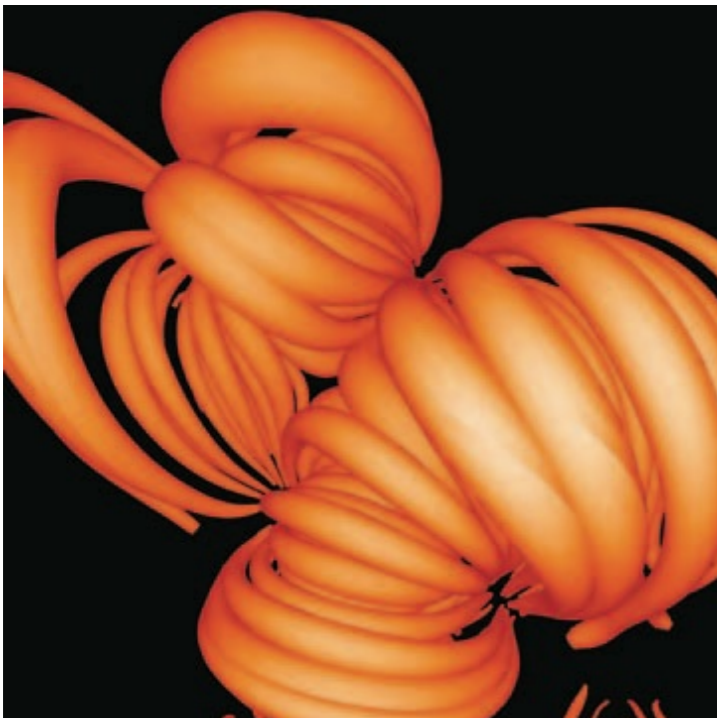
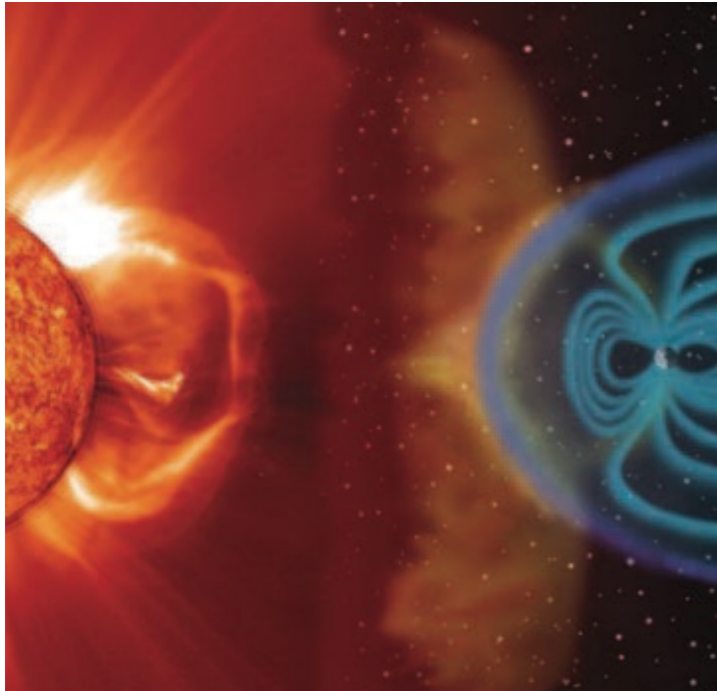
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Space Radiation

Movie Introduction.1 Radiation: and Human Space Exploration



Space Radiation



Radiation biology is an interdisciplinary science that examines the biological effects of radiation on living systems. To fully understand the relationship between radiation and biology, and to solve problems in this field, researchers incorporate fundamentals of biology, physics, astrophysics, planetary science, and engineering.

The major goal of NASA's Space Radiation Project is to enable human exploration of space without exceeding an acceptable level of risk from exposure to space radiation. Space radiation is distinct from common terrestrial forms of radiation. Our magnetosphere protects us from significant exposure to radiation from the sun and from space. Radiation that is emitted from the sun is comprised of fluctuating levels of high-energy protons. Space radiation consists of low levels of heavy charged particles. High-energy protons and charged particles can damage both shielding materials and biological systems. The amount, or dose, of space radiation is typically low, but the effects are cumulative. Solar activity fluctuates, and so the risk of exposure increases with the amount of time spent in space. Therefore there is significant concern for long-term human space travel. Possible health risks include cancer, damage to the cardiovascular system, central nervous system, cataracts, risk of acute radiation sickness, and hereditary effects. Because there is limited data on human response to space radiation, scientists have developed methods to estimate the risk. This is based on theoretical calculations

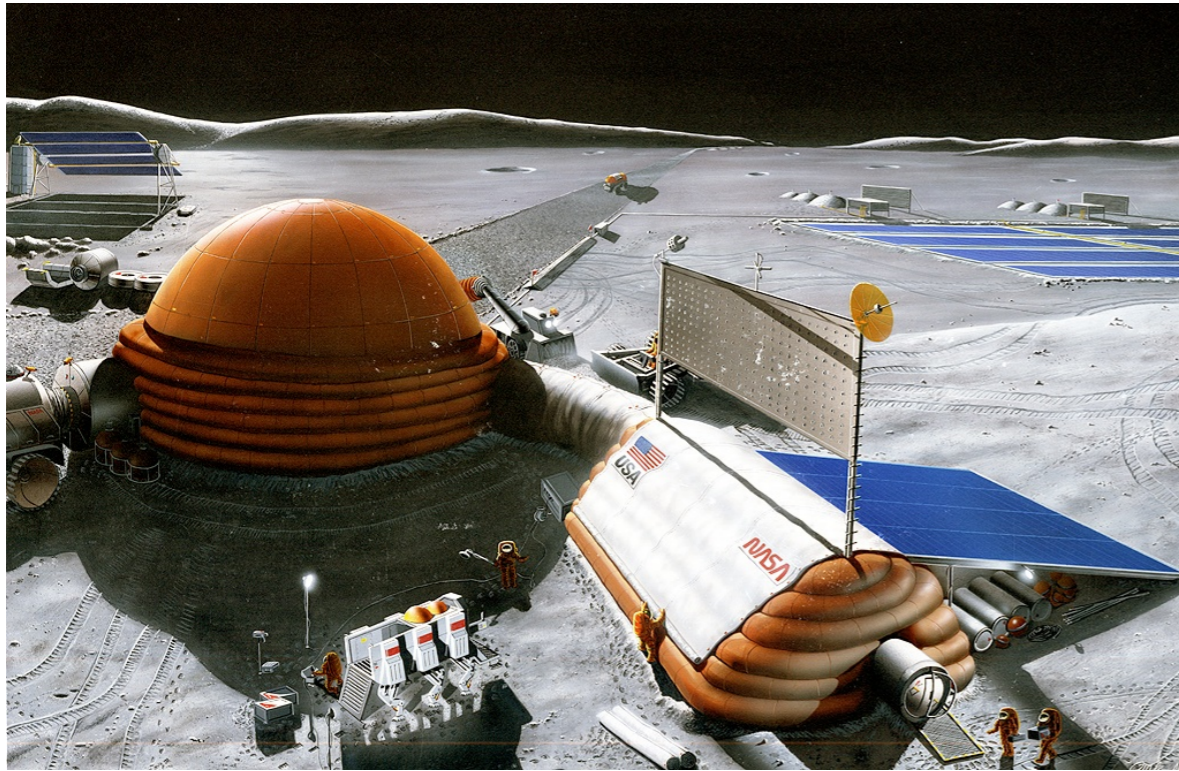


Figure i.1: An artist's conception of a future Moon base.

and biological experimentation. NASA supports research to analyze biological effects at ground-based research facilities where the space radiation environment can be simulated. Research performed at these facilities is helping us to understand and reduce the risk for astronauts to develop biological effects from space radiation, to ensure proper measurement of the doses received by astronauts on the International Space Station (ISS) and in future spacecraft, and to develop advanced materials that improve radiation shielding for future long-duration space exploration on the Moon and possibly on Mars.

For over 35 years, NASA has been collecting and monitoring the radiation doses received by all NASA astronauts who have

traveled into space as part of the Gemini, Apollo, Skylab, Space Shuttle, Mir, and ISS programs. While uncertainties in predicting the nature and magnitude of space radiation biological risks still remain¹, data on the amount of space radiation and its composition are becoming more readily available, and research is helping to identify the biological effects of that radiation.

A Brief History of Humans on the Moon

It is important to note that the NASA Apollo program was designed to land humans on the Moon and bring them safely back to Earth; it was not designed to establish a permanent presence on the Moon. The duration of the lunar surface missions were very short, largely due to the risks of space radiation exposure and the unpredictable nature of the solar weather.

Between 1969 and 1972, six of the seven lunar landing missions (including Apollo 11, 12, 14, 15, 16, and 17) were successful and enabled 12 astronauts to walk on the Moon. While on the surface, the astronauts carried out a variety of lunar surface experiments designed to study lunar soil mechanics, meteoroids, seismic activity, heat flow, lunar ranging, magnetic field distributions, and solar wind activity. The astronauts also gathered samples and returned to Earth with over 600 pounds of Moon rocks and dust. Since 1972, no human has returned to the Moon.

¹ Lancet Oncol 2006; 7:431-35

² http://spaceflight.nasa.gov/gallery/images/exploration/lunarexploration/html/s89_26097.html

Mission	Total Duration	Lunar Surface Duration	Average Radiation Dose
Apollo 11	08 days, 03 hrs, 13 mins	21 hrs, 38 mins	1.8 mGy
Apollo 12	10 days, 04 hrs, 31 mins	31 hrs, 31 mins	5.8 mGy
Apollo 14	09 days, 00 hrs, 01 mins	33 hrs, 31 mins	11.4 mGy
Apollo 15	10 days, 01 hr, 11 mins	66 hrs, 54 mins	3 mGy
Apollo 16	11 days, 01 hr, 51 mins	71 hrs, 02 mins	5.1 mGy
Apollo 17	12 days, 13 hrs, 51, mins	74 hrs, 59 mins	5.5 mGy

* Average radiation dose information can be found on the Life Sciences Data Archive at JSC.

Table shows the amount of time astronauts spent on the surface of the Moon during each lunar landing, and the average radiation dose they received.

Figure i.2 Apollo Lunar Excursion Module



Exploring the surrounding lunar landscape (see figure i.3) and traveling to remote locations on the Moon may also be part of the activities lunar explorers will perform. There are unknowns about long-duration exploration of the Moon.

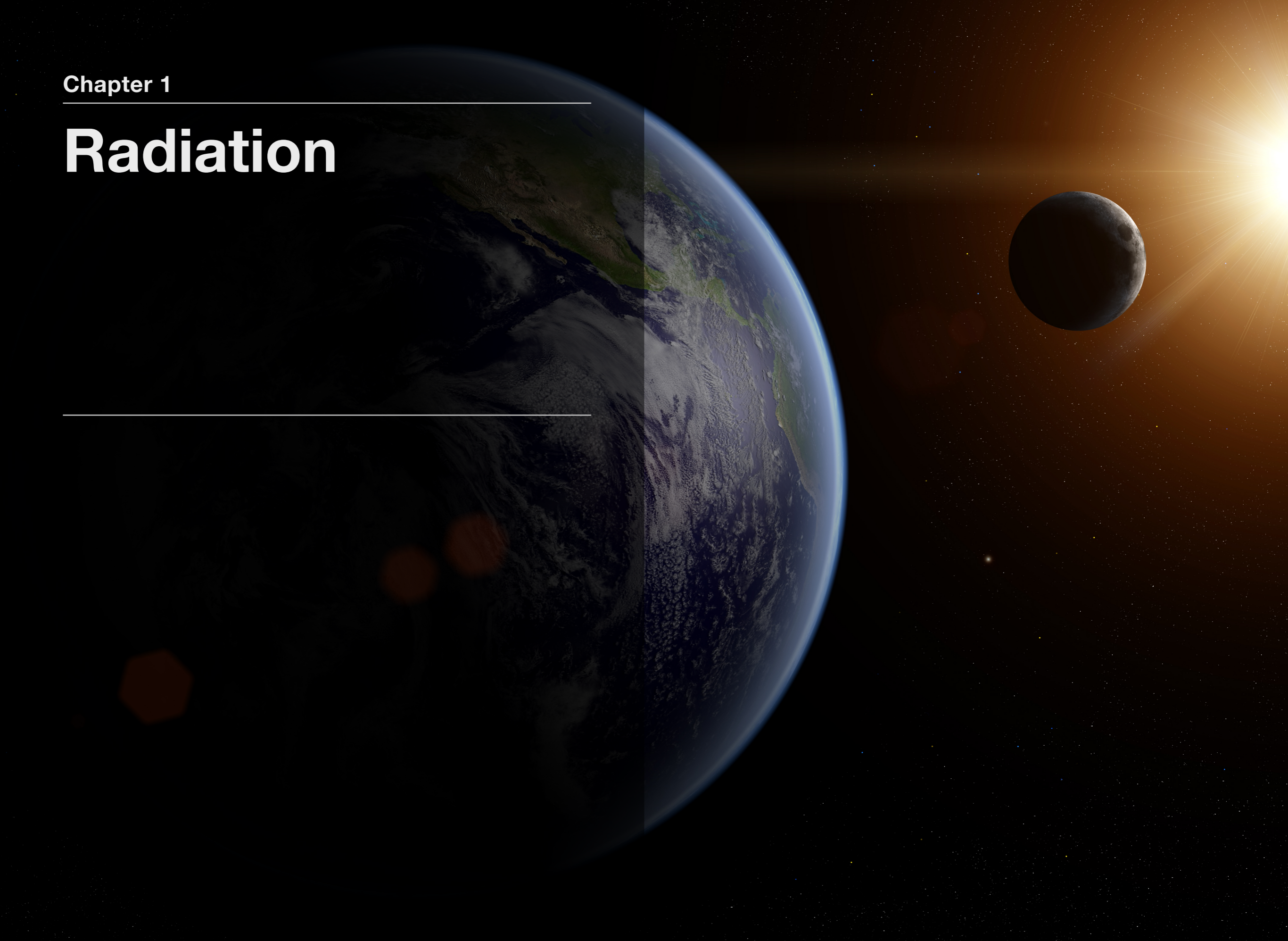
Another important concept to understand is space weather. Space weather refers to the conditions and processes occurring in space that have the potential to affect spacecraft or people in the space environment. Space weather processes include changes in the interplanetary magnetic field, coronal mass ejections, disturbances in the Earth's magnetic field, and changes in the solar wind (energy that flows from the Sun in the form of particles like protons or electromagnetic radiation). Help is needed in deciding the best time to travel in space, and which materials should be used for the spacesuits, spacecraft, and habitation units on the Moon. To provide useful planning and launch date recommendations, planners will also need to understand how the Sun's activity affects the radiation environment in the solar system.



Figure i.3: An Apollo astronaut explores the lunar surface.

Chapter 1

Radiation



Radiation Intro

Movie 1.1 Why go to Mars?



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 1.1). The shorter the

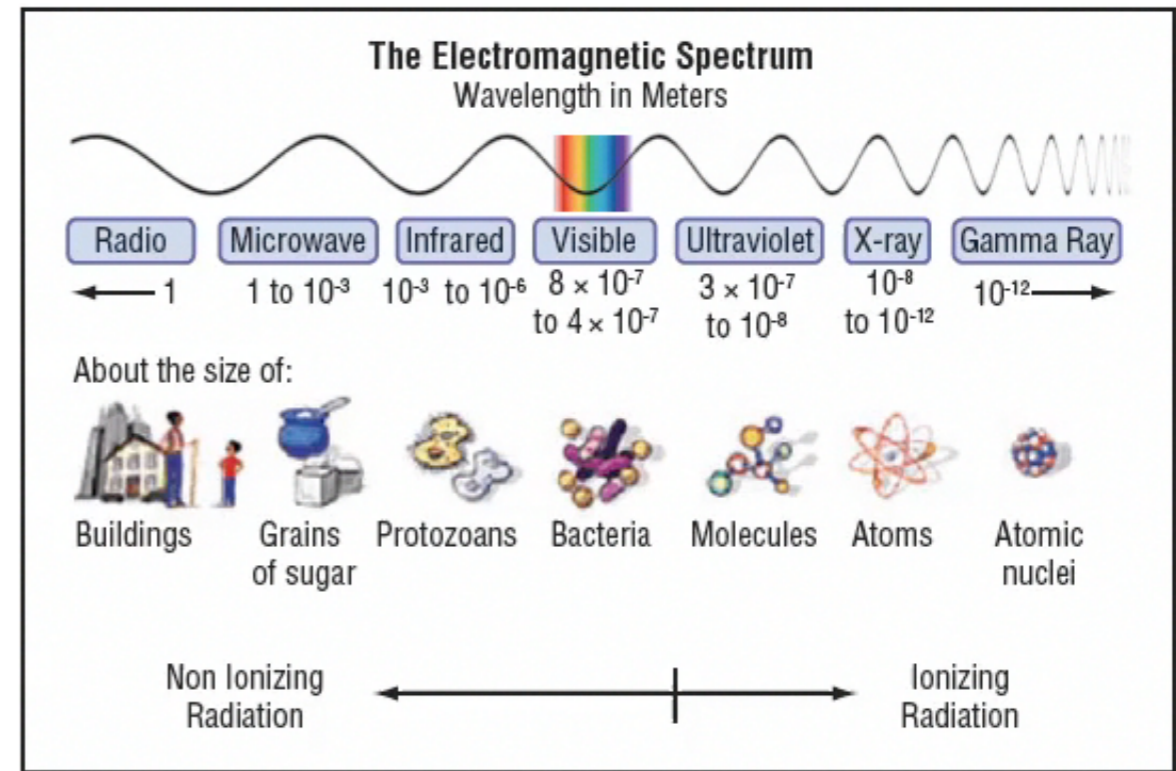


Figure 1.1: The Electromagnetic Spectrum

wavelength, the more energetic the radiation and the greater the potential for biological harm.

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 rays, and streams of protons and electrons called solar particle events (SPE)³. A robotic spacecraft called the Solar and

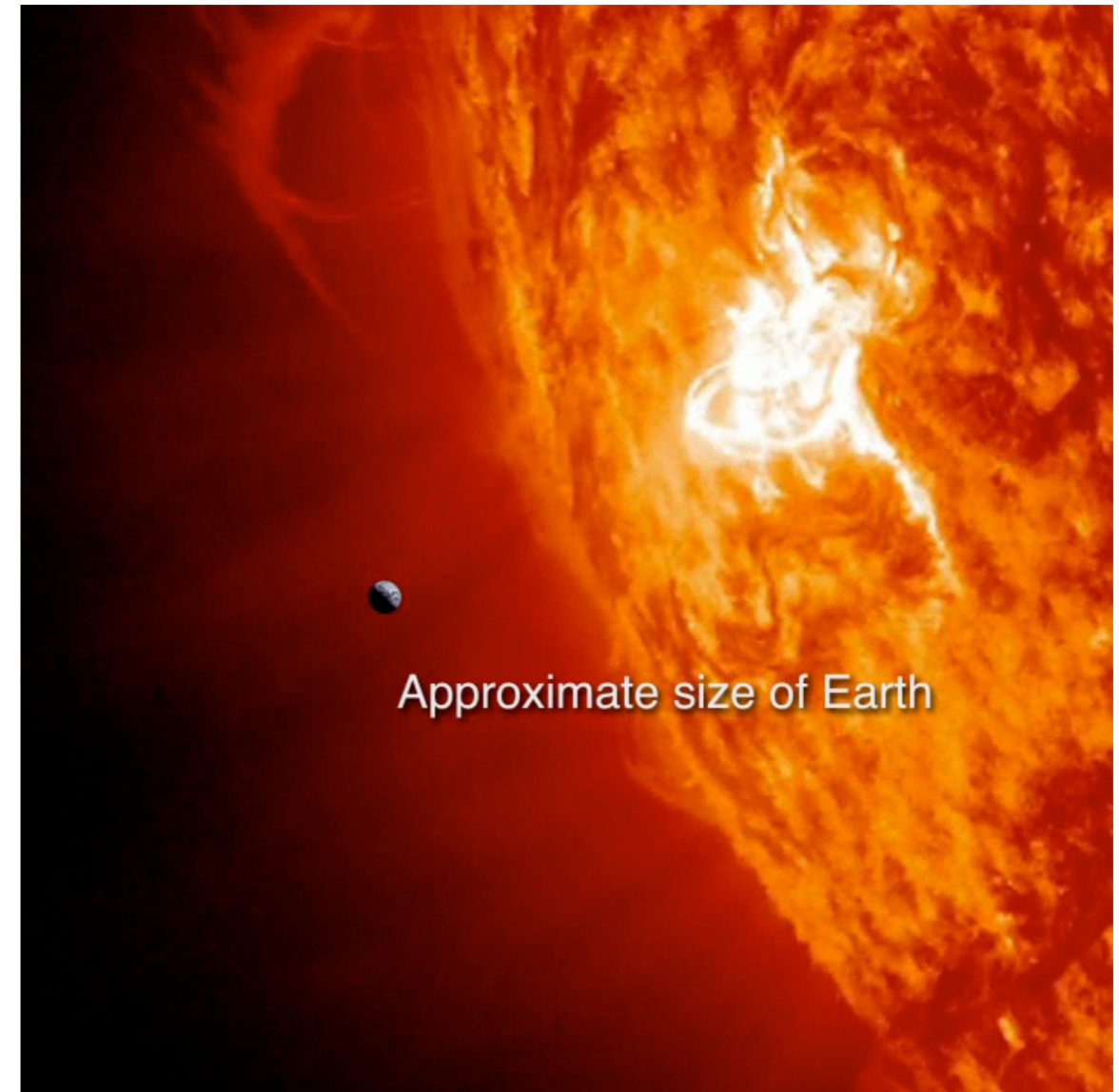


Figure 1.2: Erupting CME from the surface of the Sun.

Heliospheric Observatory (SOHO) captured an erupting CME from the surface of the Sun in the image in figure 1.2.⁴ 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.

³ <http://solarscience.msfc.nasa.gov/CMEs.shtml>

⁴ http://www.nasa.gov/vision/universe/solarsystem/perfect_space_storm.html

What Are the Different Kinds of Radiation?

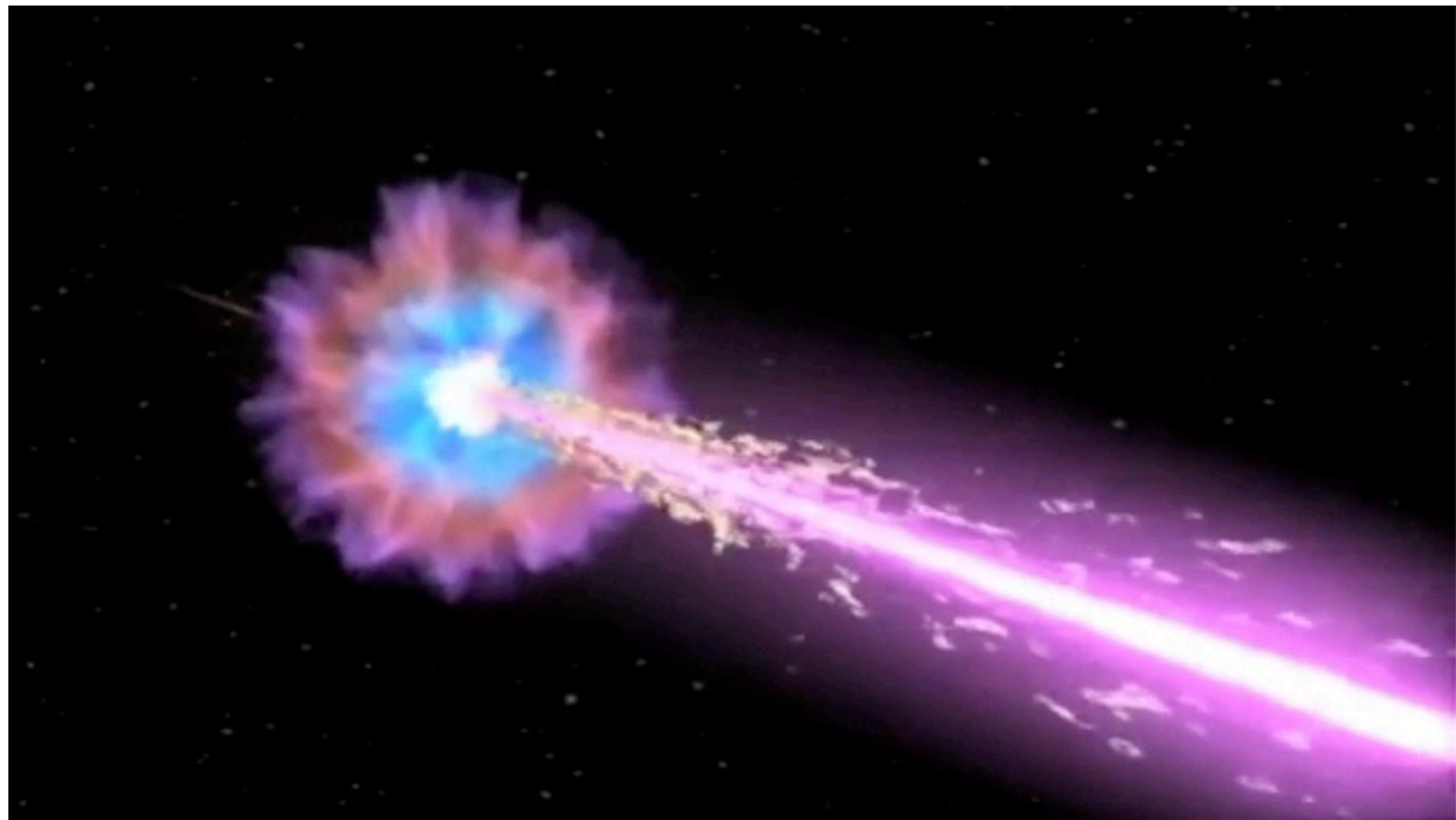
Radiation can be either non-ionizing (low energy) or ionizing (high energy). Ionizing radiation consists of particles or photons that have enough energy to ionize an atom or molecule by completely removing an electron from its orbit, thus creating a more positively charged atom. Less energetic non-ionizing 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.

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 and microwaves. 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.

Movie 1.2 What is Space Radiation?



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.⁵ 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.⁶ 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.

⁵ <http://helios.gsfc.nasa.gov/gcr.html>

⁶ http://imagine.gsfc.nasa.gov/docs/science/known_1/cosmic_rays.html

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. 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 body 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.⁷ Figure 1.3 shows GCR falling onto the surface of Mars. GCR appear as faint white dots, whereas stars appear as white streaks.

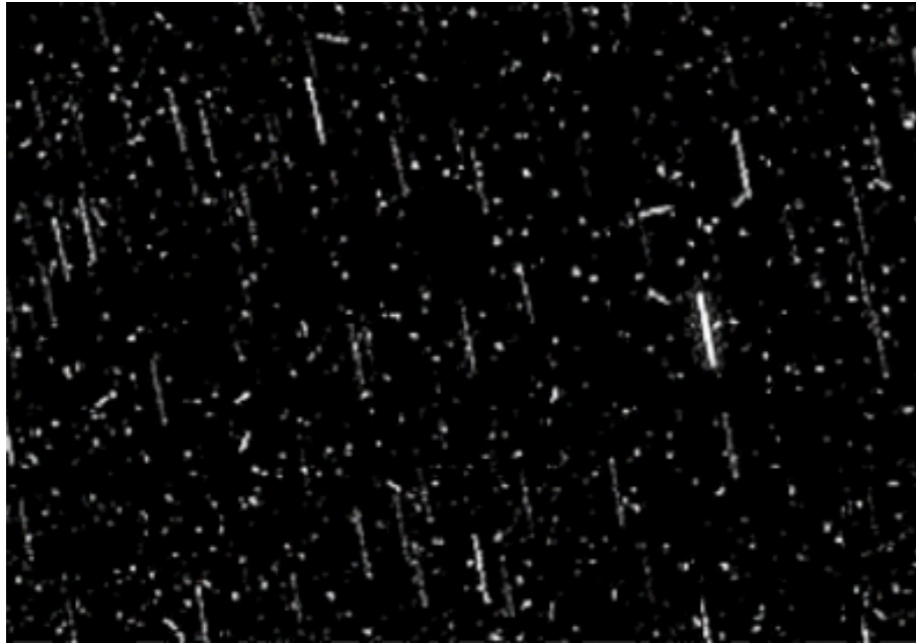


Figure 1.3: GCR appear as dots in this image. Image credit: NASA.

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.⁸

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 rings near the Earth in figure 1.4 is the approximate location of the Van Allen Belts, where high-energy radiation is trapped.

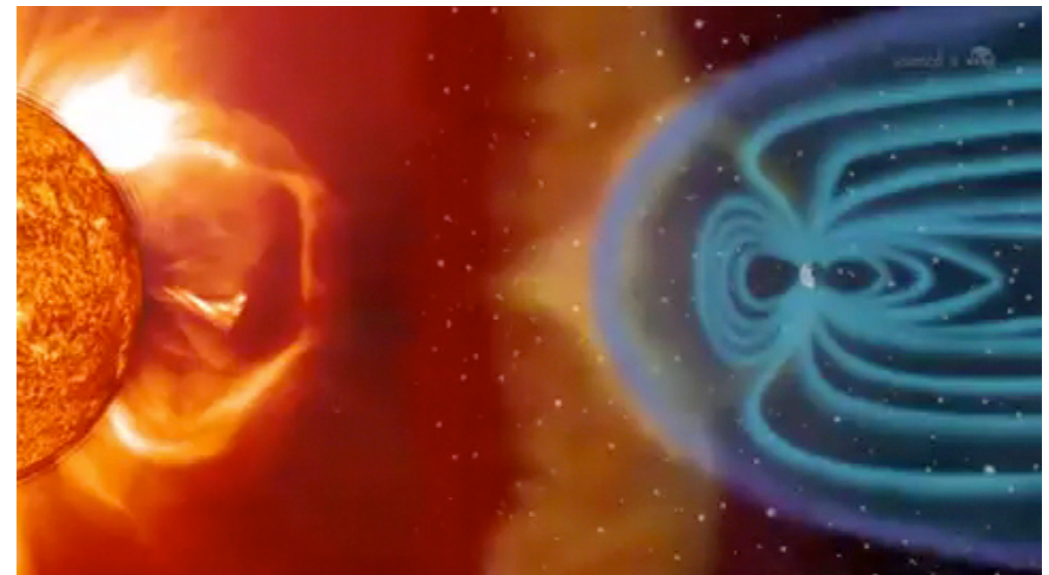
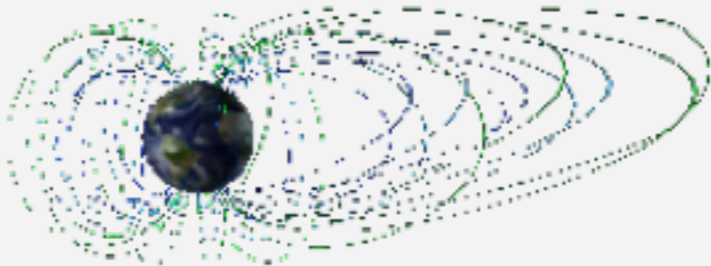


Figure 1.4: Van Allen Belts. Image Credit: NASA.

⁷ www.spaceflight.nasa.gov/spaceneeds/factsheets/pdfs/radiation.pdf

⁸ <http://www-istp.gsfc.nasa.gov/Education/Iradbelt.html>

Interactive 1.1 Van Allen Belt Model



Drag image to rotate - Pinch to expand and contract image

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:⁹

- 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.

⁹ www.spaceflight.nasa.gov/spaceneeds/factsheets/pdfs/radiation.pdf

¹⁰ <http://solarscience.msfc.nasa.gov/images/zurich.gif>

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 1.5.¹⁰

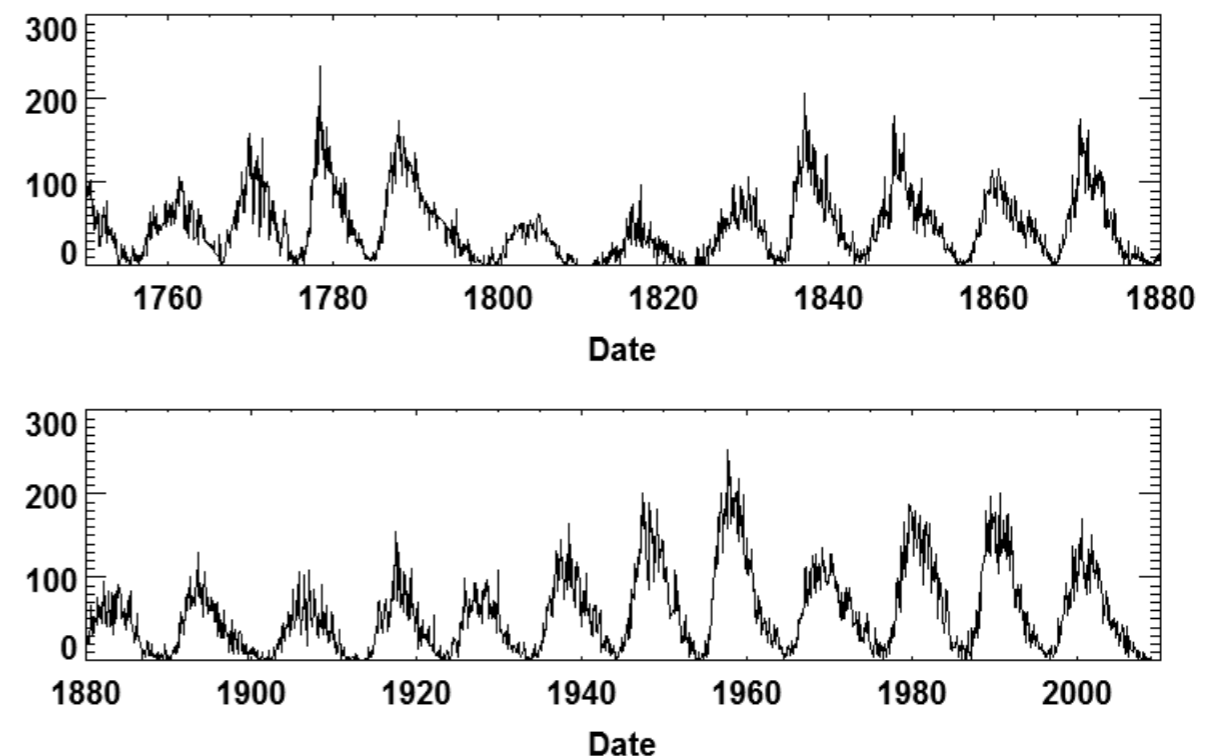


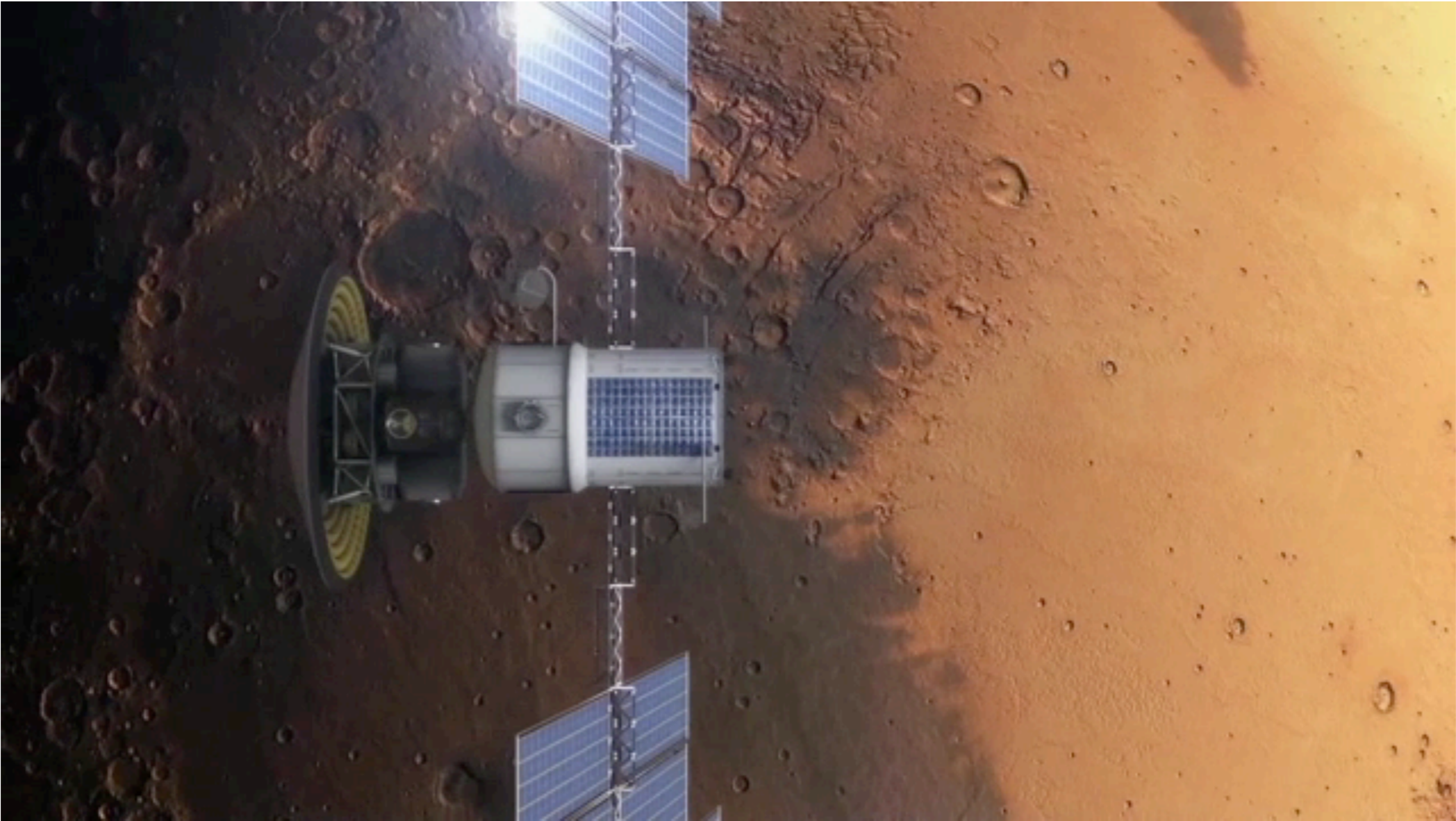
Figure 1.5: The sunspot cycle of the Sun. Image credit: NASA.

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.

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.

Movie 1.3 What is space weather?



How Is Radiation Measured?

There are several properties of radiation that must be considered when measuring or quantifying radiation. These include the magnitude of the source radioactivity, 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).

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.

¹¹ 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. In general, all these different ways to measure radiation or effective dose radiation may be considered equivalent, e.g. rad and rem and Gy and Sv.

¹¹ 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.

Movie 1.4 Evaluating Radiation Protection Plans



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 20 times higher. The NASA limit for radiation exposure in low-Earth orbit is 1000 mSv/year, or 1000 rem/year based on the astronaut's gender and age. 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.

The career biologic radiation effective 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 should be exposed to less radiation because they have more life to live, and therefore a longer chance to develop subsequent health problems.

Table 2: Exposure Limits

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.¹²

¹² srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm

Table 3: Radiation penetration and exposure limits.

Depth of Radiation Penetration and Exposure Limits for Astronauts and the General Public (in mSv)				
	Exposure Interval	Blood Forming Organs (5 cm depth)	Eyes (0.3 cm depth)	Skin (0.01 cm depth)
Astronauts	30 Days	250	1,000	1,500
	Annual	500	2,000	3,000
	Career	1,000-4,000	4,000	6,000
General Public	Annual	1	1,500	50

Table 4: Missions and radiation dose.

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
ISS Mission (up to 6 months orbiting Earth at 353 km)	160 mSv
Estimated Mars mission (3 years)	1,200 mSv

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.

Table 4 compares and contrasts various missions and their durations with the observed radiation dose.

Crews aboard the Space Station receive an average of 80 mSv for a six-month stay at solar maximum (the time period with the maximum number of sunspots and a maximum solar magnetic field to deflect the particles) and an average of 160 mSv for a six-month stay at solar minimum (the period with the minimum number of sunspots and a minimum solar magnetic field).

Although the type of radiation is different, 1 mSv of space radiation is approximately equivalent to receiving three chest x-rays. On Earth, we receive an average of 2 mSv every year from background radiation alone¹³.

How Does the Radiation Environment on Earth Compare to the Radiation Environment on the Moon and Mars?

NASA has collected a variety of radiation and environmental data from the Moon and Mars. During the Lunar Prospector mission, NASA scientists discovered that there are some areas of the Moon that have a weak magnetic field. Magnetic fields have the ability to deflect small amounts of radiation. Locations with these fields are slightly more protected and might be candidate sites for bases on the Moon. Mars also has similar magnetic fields, though greater than those of the Moon. However, these magnetic fields will not substantially change either the radiation exposure level type nor magnitude compared to the areas on the Moon or Mars. As shown in figure 1.6, the strongest magnetic fields on the Moon are located at $\approx 20^\circ\text{S}$, 170°E and $\approx 43^\circ\text{S}$, 170°E .

The Moon and Mars are still extremely vulnerable to the effects of space radiation in spite of localized magnetic fields. They do not have global magnetic fields like those of Earth. As a result, their surfaces are not shielded from SPE that erupt from the surface of the Sun. In addition, the GCR that permeates interstellar space can freely bombard the surface of the Moon and Mars.

¹³ www.spaceflight.nasa.gov/spaceneeds/factsheets/pdfs/radiation.pdf

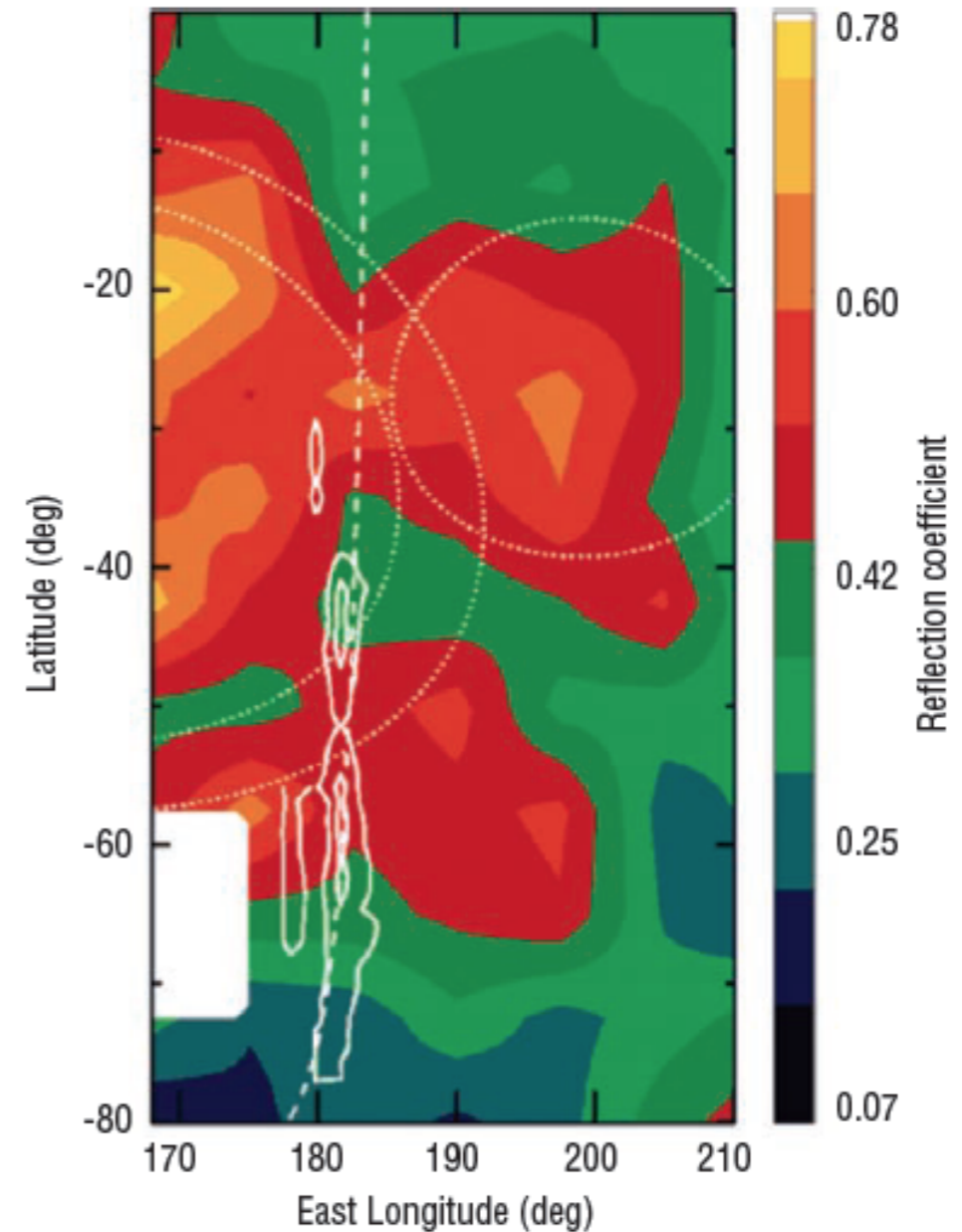


Figure 1.6: Magnetic fields on the moon. Image credit: NASA.

Finally, the Moon and Mars do not have dense atmospheres. Although Mars has an extremely thin atmosphere composed primarily of carbon dioxide, it is not thick enough to shield it from most cosmic radiation. The Moon essentially lacks an atmosphere altogether.

In order to minimize radiation exposure, people living on the Moon or Mars will need to limit the time they spend outside in their spacesuits and the distance they travel from their protective habitats. The total amount of radiation that astronauts receive will greatly depend upon solar activity, their location with respect to planetary magnetic fields, and the amount and type of radiation shielding used in habitats and spacecraft. Radiation exposure for astronauts aboard the ISS in Earth orbit is typically equivalent to an annualized rate of 20 to 40 rems (200 – 400 mSv).¹⁴ The average dose-equivalent rate observed on a previous Space Shuttle mission was 3.9 μ Sv/hour, with the highest rate at 96 μ Sv/hour, which appeared to have occurred while the Shuttle was in the South Atlantic Anomaly region of Earth's magnetic field (1 Sv = 1,000 mSv = 1,000,000 μ Sv).

For a six-month journey to Mars an astronaut would be exposed to roughly 300 mSv, or a total of 600 mSv for the round-trip. If we assume that the crew would spend 18 months on the surface while they wait for the planets to realign to make the journey back to Earth possible, they will be exposed to an additional 400 mSv, for a grand total exposure of about 1,000 mSv. Note that an astronaut repeating the same journey on multiple occasions could receive less or more radiation each time, if they are in the line of a CME or SPE.

¹⁴ <http://hrp.jsc.nasa.gov/?viewFile=program/srp>

1.1 Ionizing, Non-Ionizing, or Both?

Consider the image below then classify as using or producing **ionizing radiation**, **non-ionizing radiation**, or **both**.

Question 1 of 16

Cell Phones

- A.** Ionizing
- B.** Non-Ionizing
- C.** Both

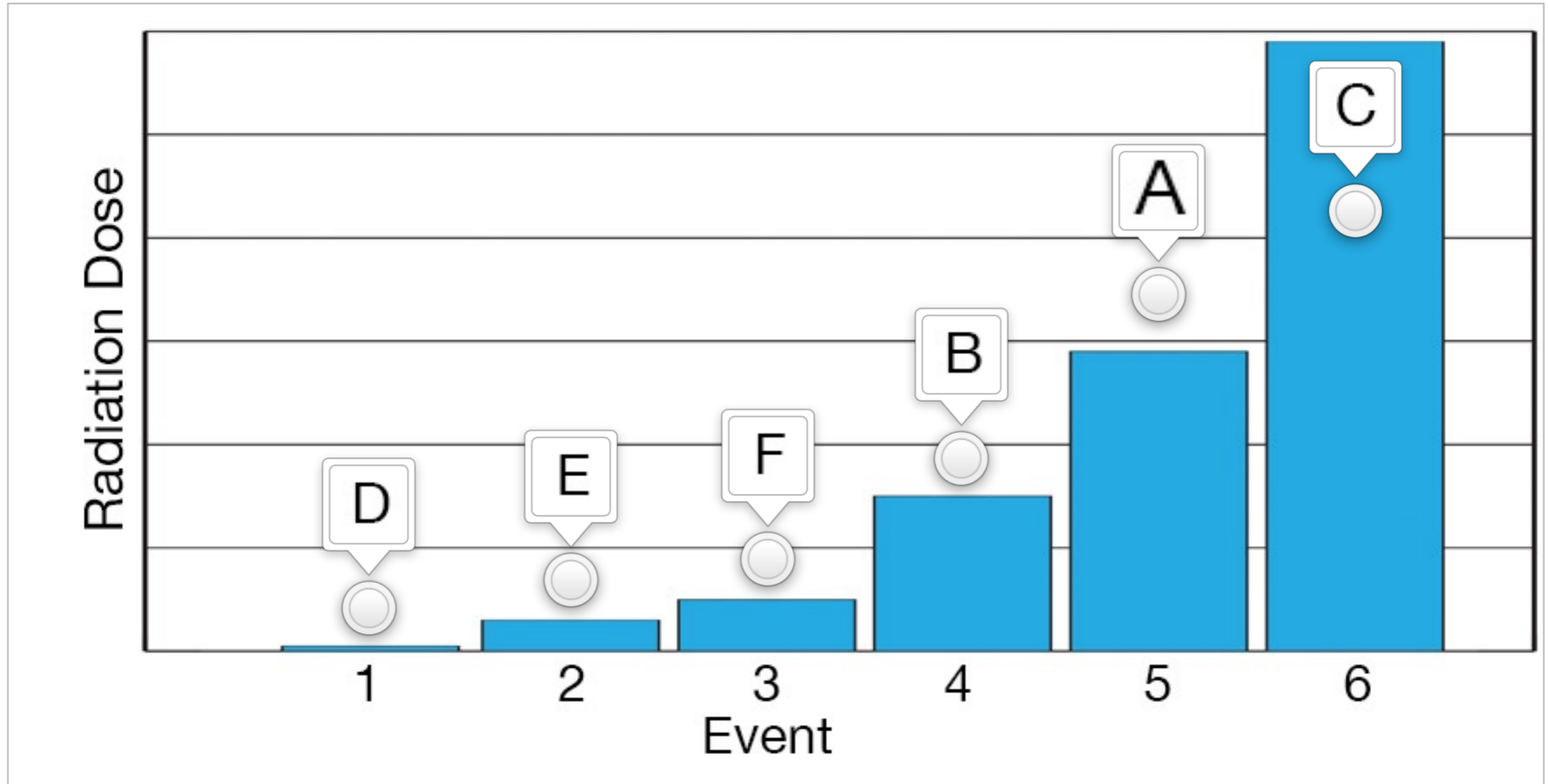


Check Answer



1.2 Matching Radiation Doses: - Match the radiation dose to the letter of the matching activity

A) 9days on Moon, B) 1 CAT Scan, C) 1yr on ISS, D) 1 Dental X-Ray, E) 1 Hip X-Ray, F) 1year on Earth



A B C D E F

Check Answer

Chapter 2

Radiation Damage in Living Organisms



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.

Movie 2.1 Radiation penetrating a deep space habitat



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 Human Research Program, Human Research 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

Movie 2.2 Radiation sources in deep space



Solar radiation emanates from our sun. Galactic cosmic radiation emanates from suns throughout the universe.

Movie 2.3 What does space radiation do to humans?





Figure 2.1: NASA Ames researchers in the Drosophila lab.

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 2.1. Careful analysis of both the flight experiment and ground controls are critical to understanding the biological changes that result from spaceflight.

Many studies are also carried out in ground-based research. However, it is not currently practical to perform either fundamental or clinical radiation research on the ISS because of the relatively low level of space radiation and the large number of specimens needed to be studied to get significant results. 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 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

in both a space or ground laboratory. 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.2.2), 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 and brain cell development, some similar behaviors, and disease genes. In fact, there is a great deal of similarity, or homology, between some of the genes in these organisms and humans.

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 damage repair on cells. Like human cells, most yeast cells effectively repair DNA damage caused by



Figure 2.2: The fruit fly is a model organism.

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. 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. 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



Figure 2.3: NASA scientists are looking for better ways to grow plants both on Earth and in space.

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.2.3).

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 more than ~0.1gy over a short time 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

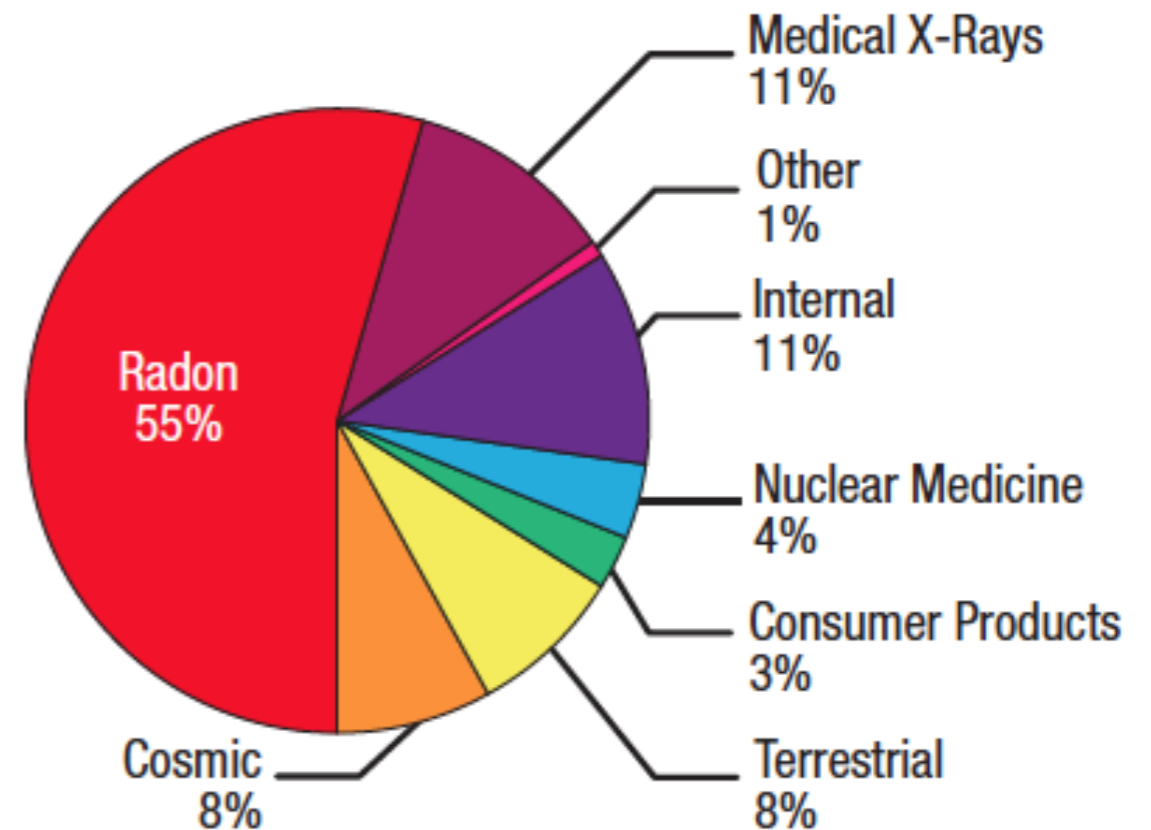


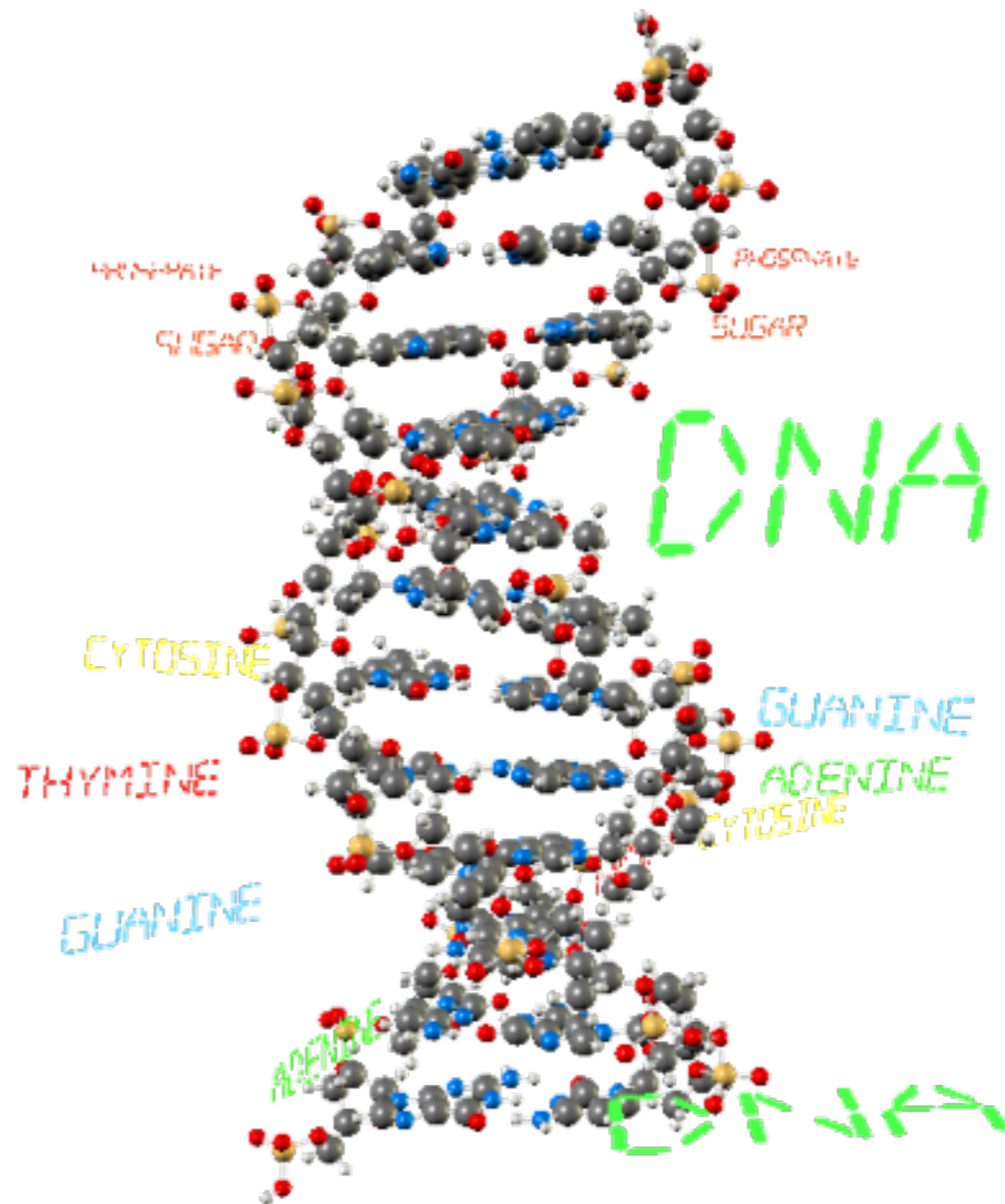
Figure 2.4: Radioactive radon gas produced from the breakdown of uranium in the Earth's crust accounts for over half of the radiation exposure to the general public. Image Credit: University of Illinois Extension.

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.

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.

Interactive 2.1 DNA Molecule



Drag inside image to rotate - Pinch to expand and contract image

What Is the Structure of DNA?

A DNA molecule (shown in fig. 2.5) 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

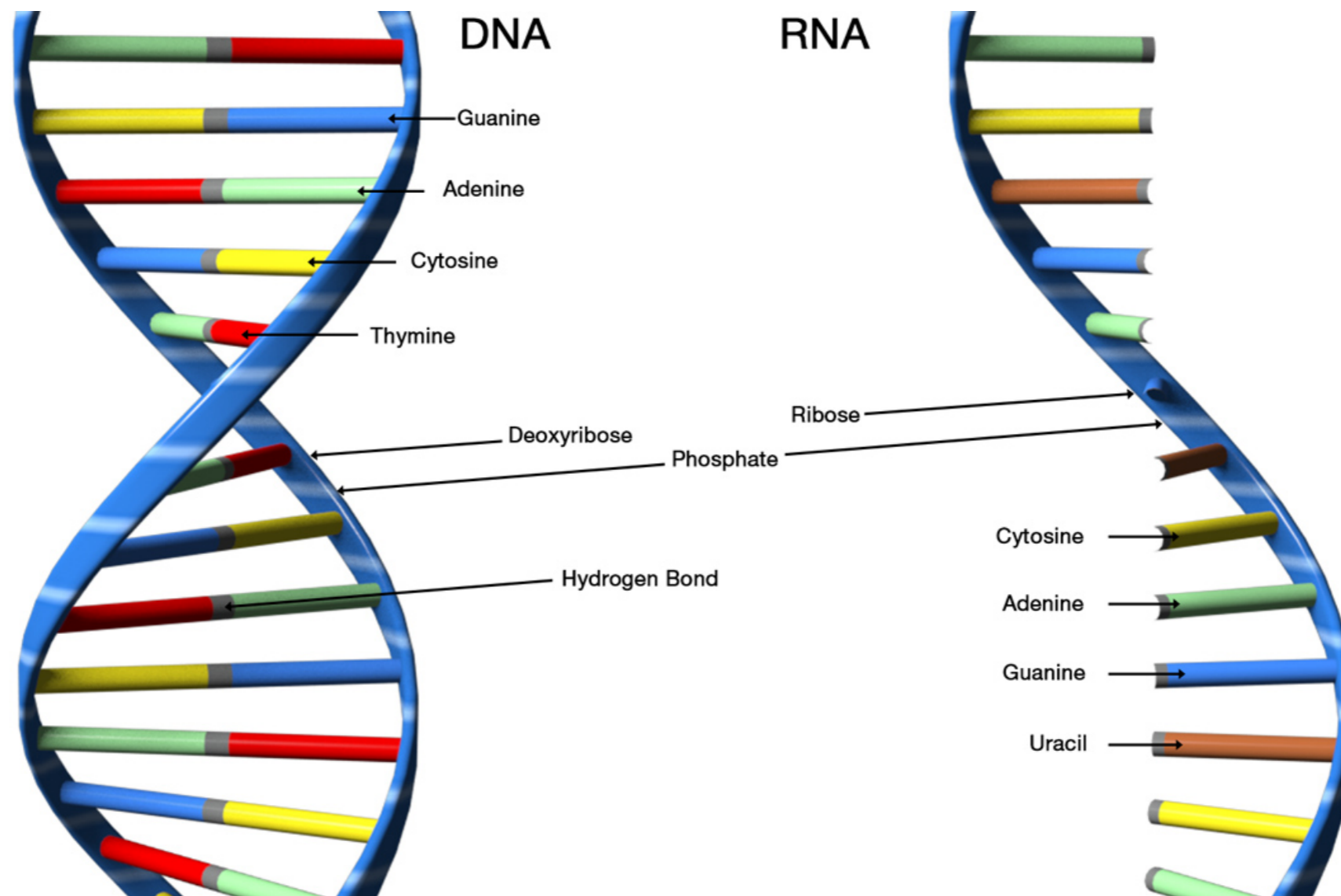


Figure 2.5: A drawing of DNA (left) and RNA (right). Image Credit: The biologycorner.com.

cells. If stretched out, the DNA of one chromosome, on average, would be about 5 cm (about 2 inches). If all DNA in a cell were lined end to end, the molecule would reach about 3 m (9.8 feet). 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.

What Is DNA's Role in Protein Production?

DNA is the storage unit for the information and is used as part of the mold 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 2.6.

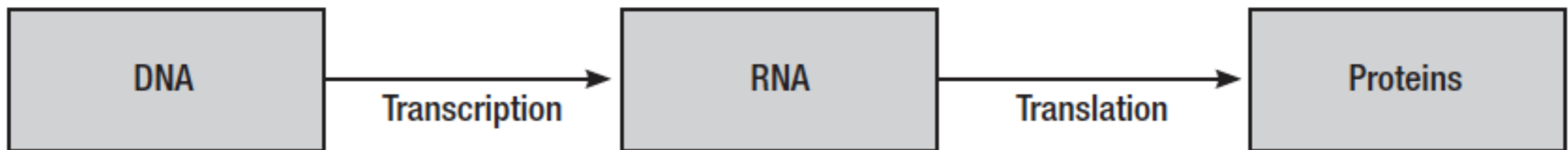


Figure 2.6: Protein production

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 2.7 shows two examples of DNA damage. Other forms of damage that can occur include the loss of a base, and a change in the base itself from oxidation or other chemical

reactions. 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 the manufacture of proteins to be started prematurely, to be stopped, or to be wrongly made. 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

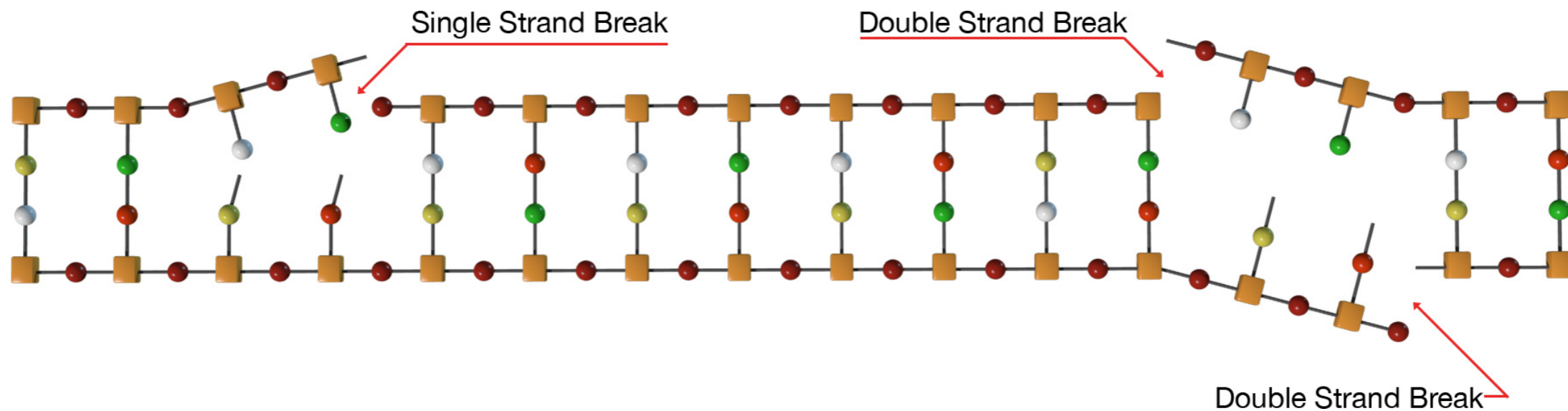


Figure 2.7: DNA model with two examples of DNA damage shown. The parallel linked sequences of orange squares(□) and red circles(○) represent the phosphate (○)- deoxyribose sugar (□) strands, or backbone, of the DNA molecule. The pairs of circles linking the two strands represent the nucleotide base pairs. In the single strand break, not that although some nucleotide base pairs have been separated, only one strand of the two DNA strands has been broken (indicated by the 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 the red arrows).

can have no effect, 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.

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 cell divisions (i.e. generations) later. Figure 2.8 is a diagram of a normal DNA molecule before and after being hit by ionizing radiation.¹⁵

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

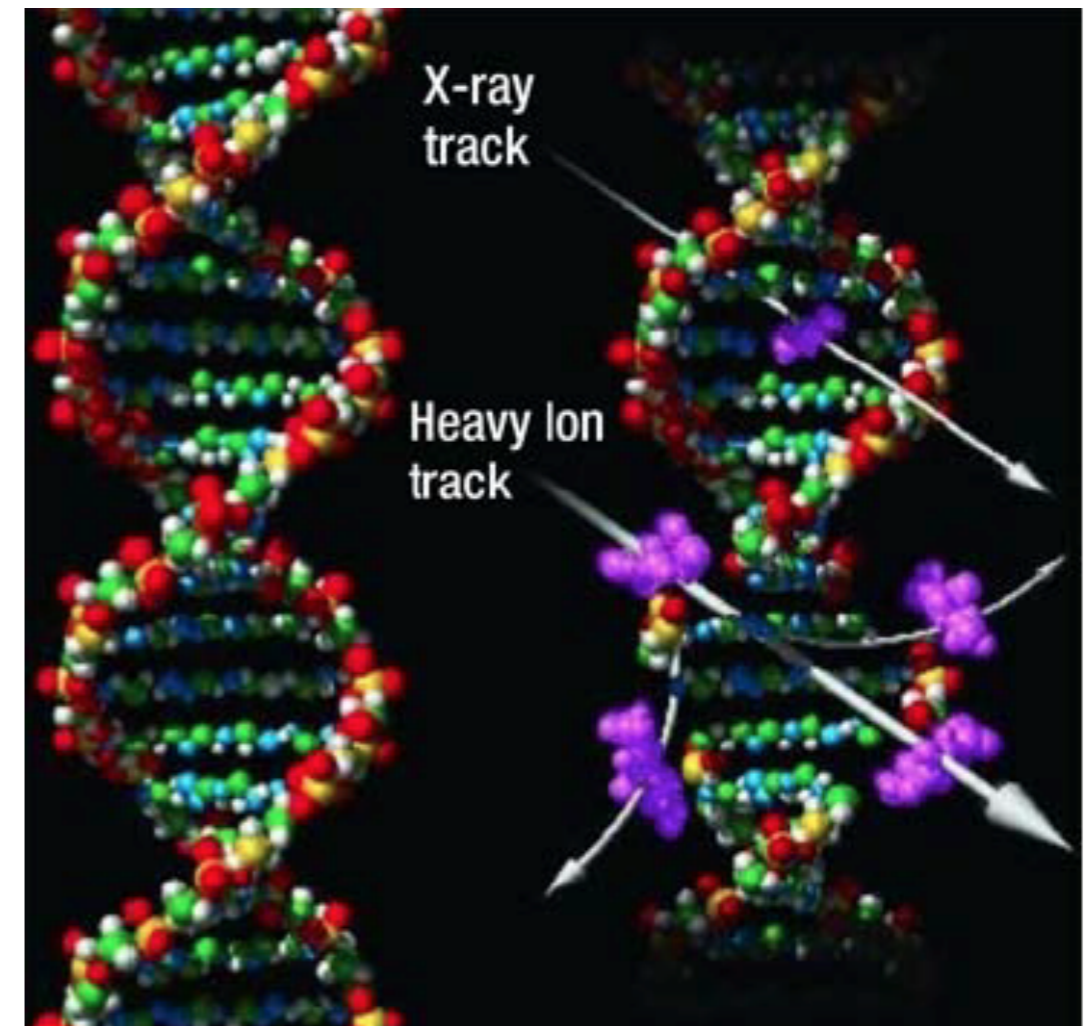
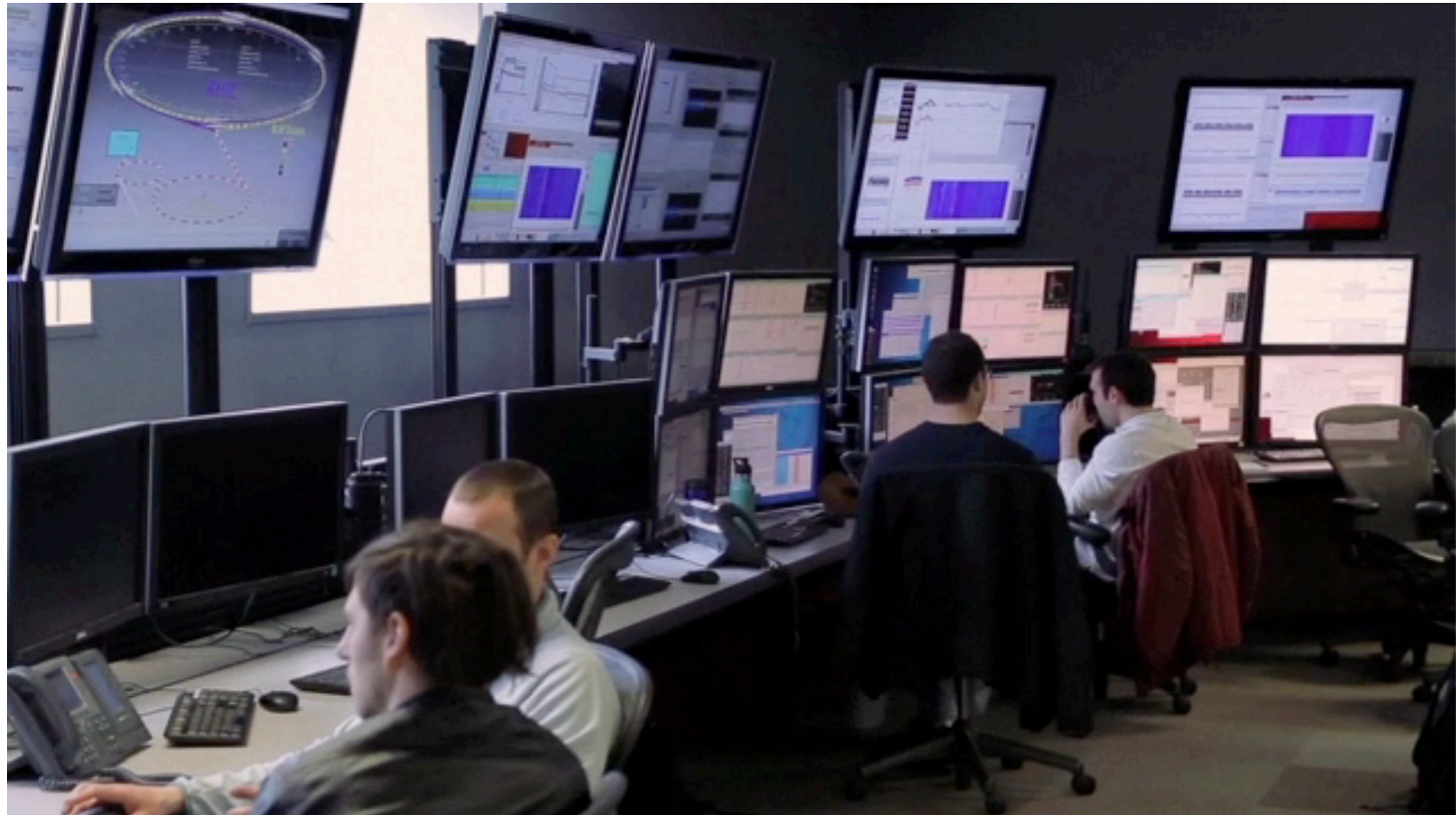


Figure 2.8: DNA before and after ionizing radiation. Image Credit: NASA

ionized, losing an electron, to give hydroxyl free radicals ($\cdot\text{OH}$). 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.

¹⁵ Cucinotta, F., Lancet Oncol 2006; 7: 431–35.

Movie 2.4 What is inside the NASA Space Radiation Laboratory?



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 damage 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



Figure 2.9: NASA Space Radiation Laboratory, at Brookhaven National Laboratory in Upton, New York.

biological risks to humans in space must rely on fundamental knowledge gathered from specialized biological and medical research.¹⁶

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. 2.9)¹⁷ and Lawrence Livermore National Laboratory 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 can result from the traverse of a single HZE particle. Examples of cellular damage are shown in figure 2.10.

¹⁶ <http://hrp.jsc.nasa.gov/?viewFile=program/srp>

¹⁷ http://www.bnl.gov/medical/NASA/NSRL_description.asp

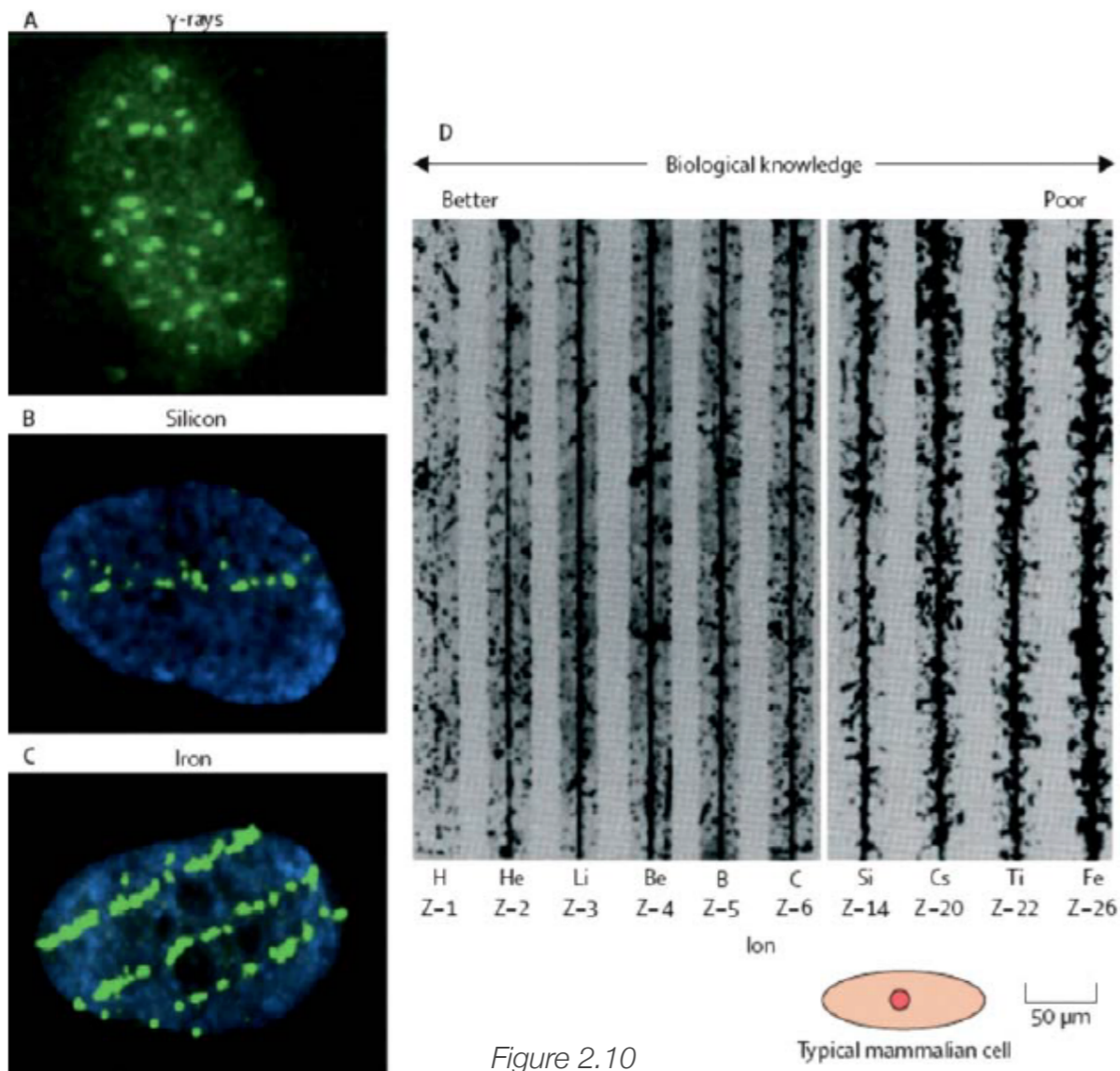


Figure 2.10

This diagram 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 from 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.

What Is the DNA Repair System?

The repair system is constantly monitoring our DNA to make sure it stays intact; proteins will congregate to sites of damage. So one way to measure DNA damage in tissues is by staining tissue samples to look for proteins involved in the repair system. This allows researchers to see where the damage occurred, and at how many sites. They can also monitor how fast the repair system takes to complete its job by staining the tissues at different times after radiation exposure. When possible, cells use the unmodified complementary strand of the DNA as a template to recover the original information. Without access to a template, cells use an error-prone recovery mechanism known as translesion synthesis as a last resort. Damage to DNA alters the three-dimensional configuration of the helix. These alterations can be detected by cellular repair mechanisms. Once damage is localized, specific DNA repair molecules move to the site. These molecules bind at or near the site of damage and induce other molecules to bind and form a complex that enables the actual repair to take place. The types of molecules involved and the mechanism of repair that assembles depend on the type of damage that has occurred and in what phase of the cell cycle that the cell is. Some examples of specific repair systems include: base excision repair (BER), which repairs damage due to a single nucleotide caused by oxidation, alkylation, hydrolysis, or deamination; and nucleotide excision repair (NER), which repairs damage affecting longer strands of 2-30 bases. This process

recognizes bulky, helix-distorting changes such as thymine dimers as well as SSBs; and mismatch repair (MMR), which corrects errors of DNA replication and recombination that result in mispaired nucleotides following DNA replication.

How Does UV Radiation Affect Us?

UV radiation is part of the sunlight spectrum of light and are wavelengths just smaller than our eyes can see. There are three kinds of UV radiation. UV-A radiation (wavelengths of 320-400 nm) plays a helpful and essential role in formation of Vitamin D by the skin. It is not absorbed by the ozone layer, and can cause sunburn and premature aging on human skin, immune system problems, and cataracts in the eyes. UV-B radiation (wavelengths of 290-320 nm), mostly impacts the surface of the skin. It is absorbed by DNA and the ozone layer, and is the primary cause of sunburn and skin cancer. After exposure to UV-B, the skin increases production of the pigment melanin. Melanin is skin pigment found in special skin cells called Melanocytes. These cells produce more melanin when exposed to UV in sunlight. The pigment absorbs the UV, preventing the UV from affecting other parts of cells and protecting your skin from UV damage. The third is UV-C, which is completely absorbed by the ozone layer and oxygen in the atmosphere. In space UV radiation level is much greater and there is no ozone layer to block it. Spacecraft windows need to be treated to prevent or significantly decrease the UV radiation from coming into the spacecraft.



Figure 2.11: DNA readily absorbs UV-B radiation.

DNA readily absorbs UV-B radiation as shown in figure 2.11.

In some cases, it causes the shape of the DNA to be changed. While cells are able to repair this damage through the use of specialized enzymes most of the time, sometimes damage is permanent and the irreparable damage has a cumulative effect that is perpetuated from then on as previously mentioned. UV damage can also cause a mutation, or change in the DNA of a gene. When this gene is transcribed and translated into a protein, the protein may contain an error that causes it be misshapen,

function improperly, lead to cancer, or even cause cells to kill themselves.¹⁸

One in five Americans will develop skin cancer and one American dies from this disease every hour. People who have had several blistering sunburns before age 18 are at higher risk of developing melanoma, the most serious form of skin cancer. Individuals with fair skin and freckles have a higher risk of developing skin cancer, but dark-skinned individuals can also get this cancer. Regardless of your skin color, exposure to UV radiation can lead to premature aging of the skin, causing it to become thick, wrinkled, and leathery. Proteins in the lens of the eye can also be altered by radiation, leading to the formation of cataracts that can lead to partial or complete blindness. UV radiation may also suppress proper functioning of the body's immune system. Warnings to protect your eyes during a solar eclipse is because the UV radiation can burn and destroy the visions in the eye.

How Do Sunscreens Work?

Sunscreens act like a very thin shield by stopping the UV radiation before it can enter the skin and cause damage. Some sunscreens contain organic molecules (such as oxybenzone, homosalate, and PABA) that absorb UV-B and/or UV-A radiation. Others use inorganic pigments (such as titanium dioxide and zinc oxide or both) that absorb, scatter, and reflect both UV-A and UV-B light. Sunscreens are labeled with a Sun Protection Factor (SPF) rating that could also be thought of as a sunburn protection

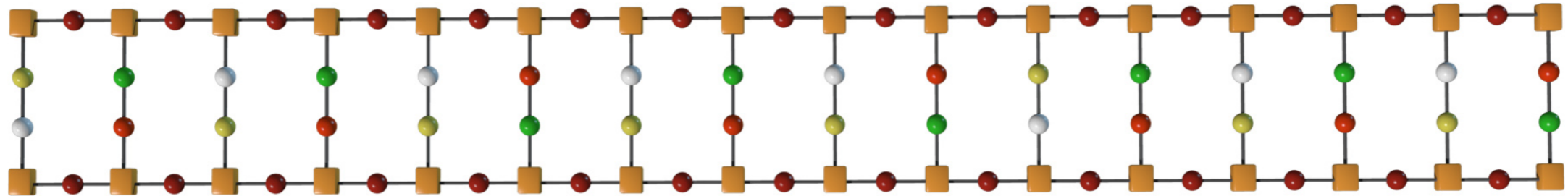
¹⁸ <http://earthobservatory.nasa.gov/Library/UVB/>

factor. For example, suppose that your skin begins to redden after 10 minutes in the sun. If you protected it with an SPF 15 sunscreen, it would take 15 times as long, or 2.5 hours, to get a comparable burn. Remember, SPF relates only to UVB protection; there is no standard measurement or rating for UV-A protection in the United States.

Review 2.1 Modeling Radiation Damaged DNA

Question 1 of 12

How many strands of nucleotides make up DNA?



- A.** 2
- B.** 4
- C.** 10
- D.** 16



Check Answer



Chapter 3

Protection from Radiation



Protection from Radiation

Protection from Ionizing Radiation

Space radiation can penetrate habitats, spacecraft, equipment, spacesuits, and can harm astronauts. Minimizing the physiological changes caused by space radiation exposure is one of the biggest challenges in keeping astronauts fit and healthy as they travel through the solar system. As mentioned previously, ionizing radiation is a serious problem that can cause damage to all parts of the body including the central nervous system, skin, gastrointestinal tract, skeletal system, and the blood forming organs. However, biological damage due to radiation can be mitigated through implementation of countermeasures that are designed to reduce radiation exposure and its effects. In this section, we will discuss the use of radiation dosimetry and operational, engineering, and dietary countermeasures.



Why is NASA Studying Radiation Countermeasures?

Radiation protection is essential for humans to live and work safely in space. To accomplish this challenging task, NASA has developed the Radiation Health Program. The goal of the program is to carry out the human exploration and development of space without exceeding acceptable risk from exposure to ionizing radiation. Legal, moral, and practical considerations require that NASA limit risks incurred by humans living and working in space to acceptable levels.¹⁹ To determine acceptable levels of risk for astronauts, NASA has adopted the standard radiation protection practices recommended by the U.S. National Council on Radiation Protection and Measurements.²⁰

What is Radiation Dosimetry?

In low Earth orbit, astronauts lose the natural shielding from solar and cosmic radiation provided by the Earth's atmosphere. In deep space astronauts also lose the shielding provided by the Earth's strong magnetic field. So, to achieve the goal of the

¹⁹ <http://srag.jsc.nasa.gov>

²⁰ http://www.nasa.gov/audience/foreducators/postsecondary/features/F_Understanding_Space_Radiation_prt.htm



Figure 3.1: NASA uses an anatomical model of a human torso and head that contains more than 300 radiation sensors.

NASA Radiation Health Program, it is necessary to monitor the radiation environment inside and outside a manned spacecraft.

An important part of every manned mission is radiation dosimetry, which is the process of monitoring, characterizing, and quantifying the radiation environment where astronauts live and work. Radiation physics support during missions also includes: calculated estimates of crew exposure during extra-vehicular activity; evaluation of any radiation-producing equipment carried on the spacecraft; and comprehensive computer modeling of crew exposure. Space station crew members routinely wear physical dosimeters to measure their accumulated exposure and, post flight, provide a blood sample to measure radiation damage to chromosomes in blood cells. In addition, experiments on the Space Station have been carried out using a synthetic human torso, which has over 300 strategically placed dosimeters to determine the levels of cosmic radiation absorbed by specific organs in the human body during space flight. Active monitoring of space radiation levels within the Space Station is achieved with dosimeters both to identify the best-shielded locations within the Space Station and to give early warning should radiation levels increase during a mission due to solar storms.

All these sources of information are carefully analyzed before, during, and after to help mission planners mitigate the four significant radiation-related health risks that are described in the NASA Human Research Roadmap: cancer, radiation damage to

<https://humanresearchroadmap.nasa.gov/>

the central nervous system, chronic and degenerative tissue diseases, and acute radiation sickness. See the previous section for information on the biological effects of radiation.

What Are Operational Countermeasures?

Currently, the main operational countermeasures against the adverse effects of radiation is simply the thickness of the ISS exterior to decrease usual solar radiation, establishing a radiation safe haven for solar flare activity, and limiting the time as astronaut can spend as a radiation worker in space. Limiting an astronaut's time in space is based on monitoring their previous radiation exposures (on orbit and during the EVA during one or more missions and other radiation exposures) and assigning them to appropriate mission lengths. Overall mission lengths on the ISS is about 6 months and may last up to one year. However, since future long-term missions of exploration to the Moon and beyond will both take longer (a round-trip to Mars will last at least two years) and expose astronauts to a more damaging types of radiation, other strategies are necessary to make sure astronauts can safely spend extended periods in deep space.

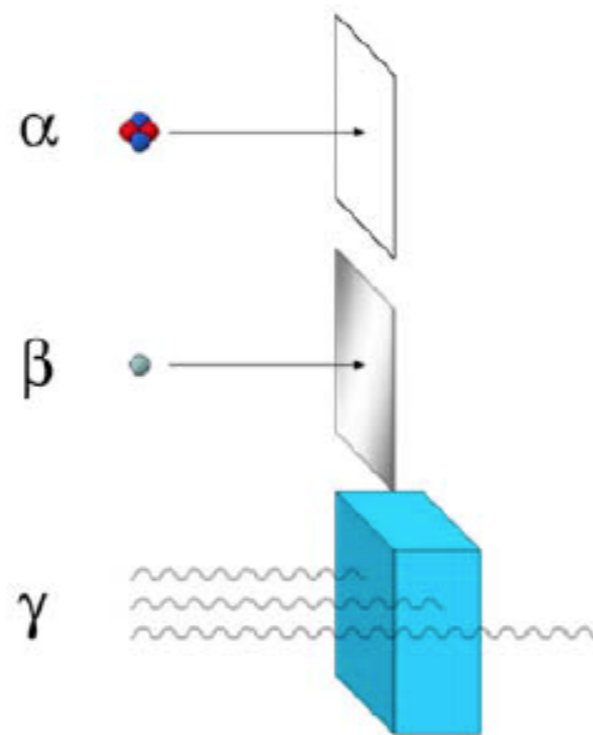


Figure 3.2: The composition and thickness of a material affects its ability to shield radiation.

What Are Engineering Countermeasures?

Engineering countermeasures are structures or tools that are designed to shield astronauts from radiation. Depending on where astronauts are living and working, the radiation shielding requirements will vary because of exposure to different types and levels of radiation. The most penetrating ionizing radiation (gamma rays and galactic cosmic rays) can pass through aluminum but is stopped by thick and dense material such as cement. In general, the best shields will be able to block a spectrum of radiation. Aboard the space station, the use of hydrogen-rich shielding such as polyethylene in the most frequently occupied locations, such as the sleeping quarters and the galley, has reduced the crew's exposure to solar radiation. Since the International Space Station, is in low Earth orbit, where the quantity and energy of the radiation is lower than in deep space because the Earth's atmosphere provides protection, this spacecraft requires less shielding than a base on the surface of the Moon. On the Moon, radiation shields would need to be very thick to prevent the cosmic rays (high-energy protons and heavy ions) from penetrating into habitation modules where astronauts will live. Such shielding could include the metal shell of a spacecraft or habitation module and an insulating layer of lunar soil (regolith) or water.

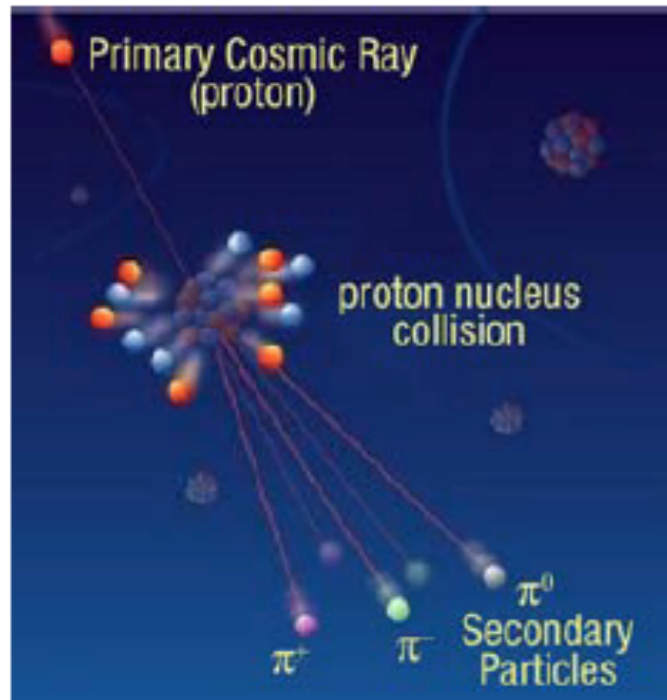


Figure 3.3: Collisions between high-energy radiation and shielding can produce damaging secondary particles.

Problems with shields arise when space radiation particles interact with the atoms of the shield itself. These interactions lead to more nuclear particles. These byproducts are called secondary particles and therefore add to the damaging radiation levels. If the shield isn't thick enough to contain them, the secondaries that enter

the spacecraft can be worse for astronauts' health than the primary space radiation. Surprisingly, heavier elements such as lead produce more secondary radiation than lighter elements such as carbon and hydrogen. Consequently, a great deal of research has been performed on a lightweight polyethylene plastic, called RFX1, which is composed entirely of lightweight carbon and hydrogen atoms. Research shows that polyethylene is 50% better at shielding solar flares and is 15% better at shielding galactic cosmic radiation as compared to aluminum. Water is another hydrogen-rich molecule that can absorb radiation. However, the oxygen content in water makes it a lot heavier than polyethylene, and therefore is much more expensive to launch. Generally, lighter shields can greatly reduce the

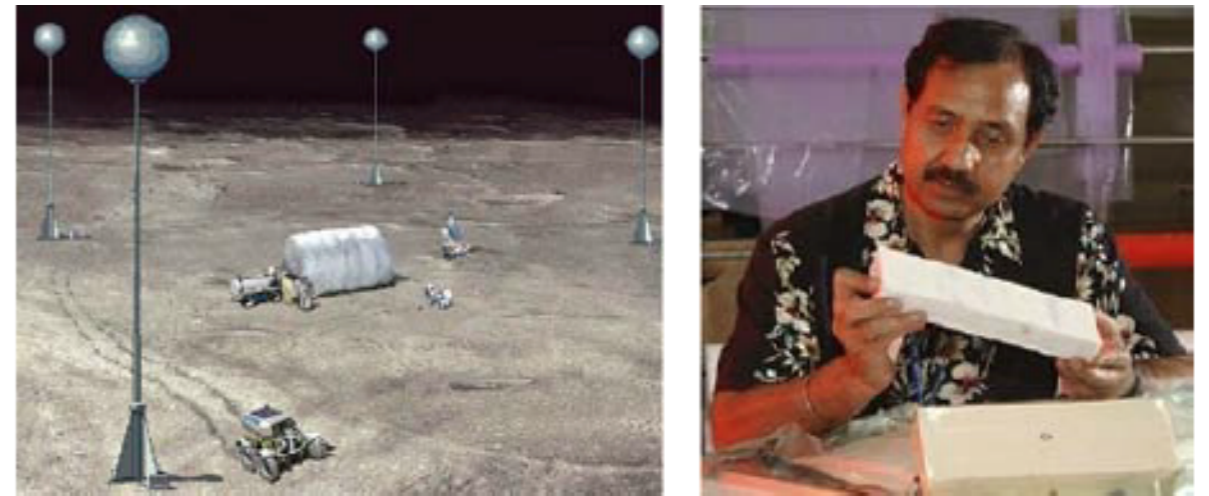


Figure 3.4: NASA has investigated electrostatic and plastic shielding. Combinations of different engineering, operational, and dietary countermeasures help improve radiation protection. Image Credit: NASA Goddard Space Flight Center.

harmful effects of incoming space radiation particles, but they cannot completely stop them.

NASA scientists have also investigated the development of electrostatic radiation shields,²¹ which generate positive and negative electric charges that deflect incoming electrically charged space radiation.

²¹ <http://www.nasa.gov/centers/goddard/news/topstory/2004/0930grb.html>

Although existing shielding can solve some radiation concerns, it makes spacecraft heavy and expensive to launch. Moreover, it does not provide complete protection against radiation. Shields five to seven centimeters thick can only block 30 to 35 percent of the radiation, which means that astronauts could still be exposed to up to 70 percent of the radiation that passes through the shields.²² For this reason, NASA is also investigating the use of medical and dietary supplements to mitigate the effects of ionizing radiation.

NASA has investigated electrostatic and plastic shielding. Combinations of different engineering, operational, and dietary countermeasures help improve radiation protection. Image Credit: NASA Goddard Space Flight Center.

What are Dietary Countermeasures?

Dietary countermeasures are foods or drugs, that when ingested by an astronaut, may have the potential to reduce effects of ionizing radiation. These supplements can be broadly categorized into two groups. The first group includes specific nutrients that prevent the radiation damage. For example, antioxidants like vitamins C and A may help by soaking up radiation-produced free-radicals before they can do any harm. Research has also suggested that pectin fiber from fruits and vegetables, and omega-3-rich fish oils may be beneficial countermeasures to

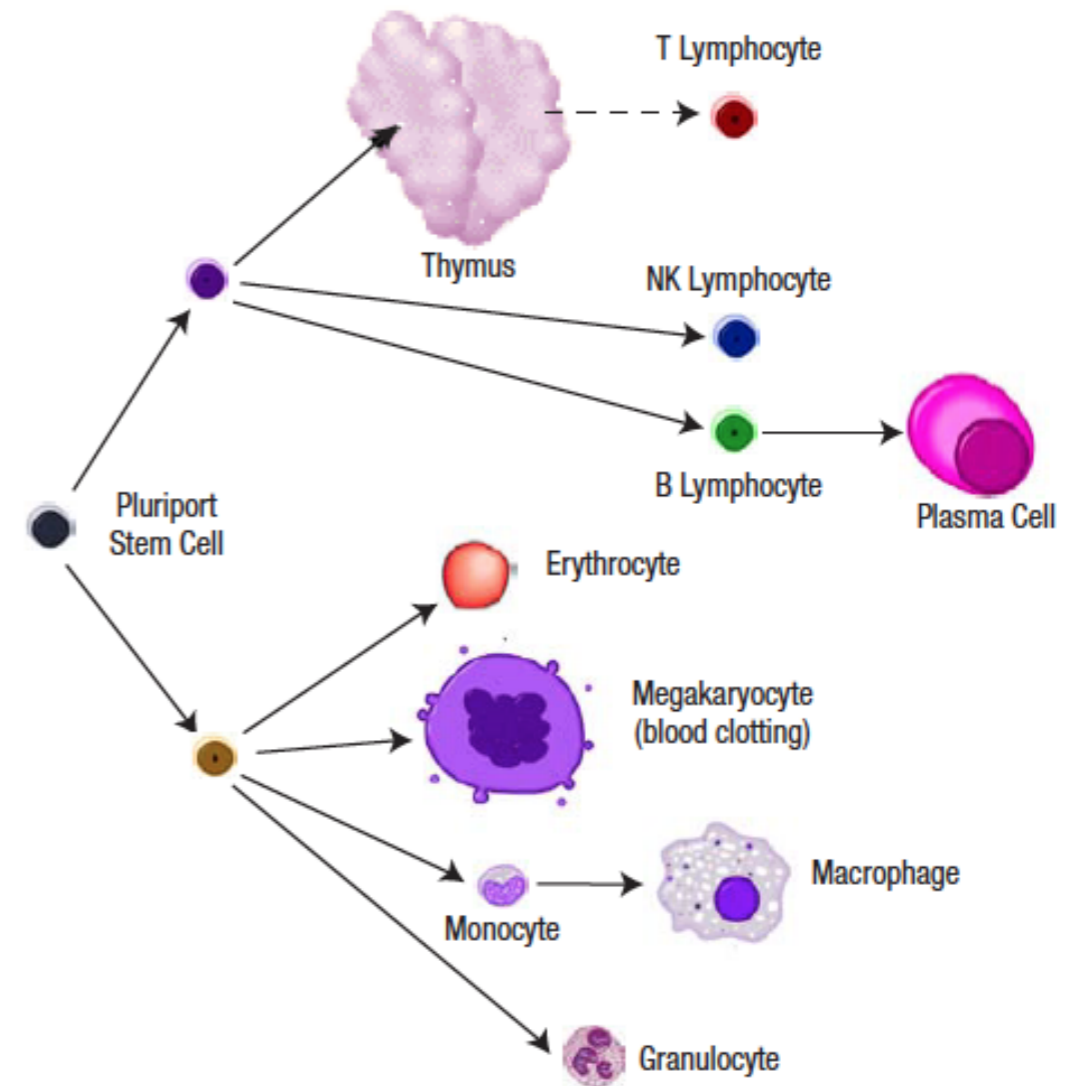


Figure 3.5: Stem cells in the bone marrow produce a wide range of blood cell types. Image Credit: Stem Cell World.

damage from long-term radiation exposure. Other studies have shown that diets rich in strawberries, blueberries, kale and spinach prevent neurological damage due to radiation. In addition, drugs such as Radiogardase (also known as Prussian blue) that contain Ferric (III) hexacyanoferrate (II) are designed to

²² http://www.nasa.gov/vision/space/travelinginspace/keeping_astronauts_healthy_prt.htm

increase the rate at which radioactive substances like cesium-137 or thallium are eliminated from the body.

The second group of dietary agents currently being considered for protection against ionizing radiation includes drugs that can facilitate faster recovery from radiation damage. These dietary agents offer protection by stimulating the growth of surviving stem and progenitor cells, or by lengthening the duration of the cell cycle segment that checks for and repairs damaged genes.²³ Some of these drugs (radioprotectants) are now used to treat people exposed to radiation contamination on Earth they may be

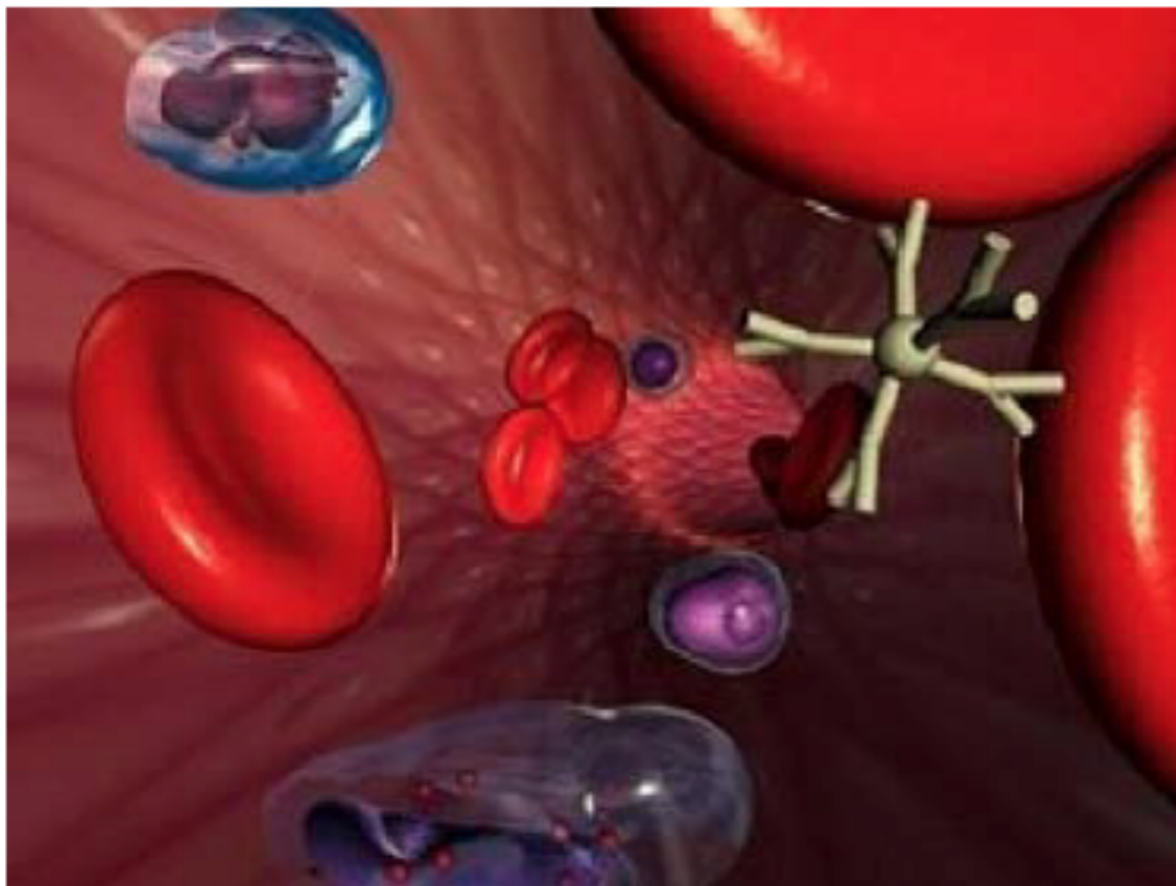


Figure 3.7: Dietary countermeasures have effects at the molecular level.
Image Credit: NASA.

good candidates for use on long duration space missions. It is important to note, however, that when administered in effective concentrations, some radioprotectants also have limiting negative side effects such as nausea, hypotension, weakness, and fatigue.

One natural defense system is for an abnormal radiation damaged cell to self-destruct before the cell becomes cancerous; this is achieved by activation of the cell's apoptosis gene (programmed cell death). Apoptosis can also be triggered intentionally by exposing the cell to enzymes or specific messengers that bind to a cell's death receptors. Other approaches that may also be useful aim to enhance the DNA repair system and immunoresponse by facilitating faster recovery of cell populations damaged by radiation. There are several such pharmaceuticals now in clinical trials. Some drugs, for example, stimulate the immune system to "restore and repopulate" bone marrow cells after radiation exposure. Other drugs appear to reduce gene mutations resulting from radiation exposure.

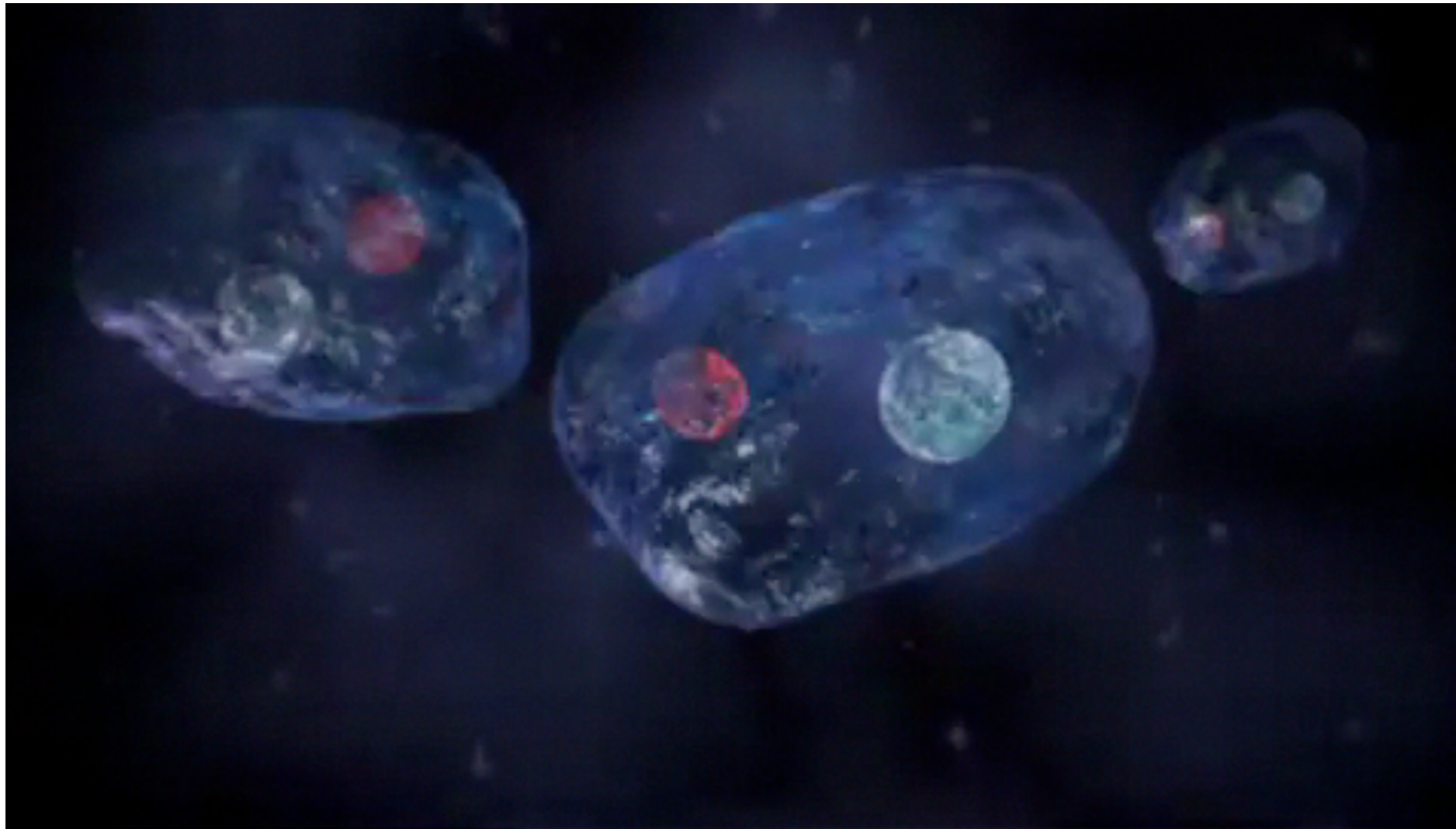
Some radiation protectants originally developed to protect military personnel in the event of nuclear warfare are now being used to protect cancer patients against the harmful effects of radiation treatment. Although large doses of radiation are damaging, small amounts of non-ionizing radiation are required for some biological processes. For example, vitamin D, necessary

²³ http://www.nasa.gov/vision/space/travelinginspace/keeping_astronauts_healthy_prt.htm

for maintenance and growth of bones, is normally produced in a person's skin through exposure to ultraviolet light. Since the Space Station is shielded to keep out harmful amounts of ultraviolet radiation from the sun and in the absence of full spectrum lighting within the ISS, normal vitamin D production in

an astronaut's skin is inhibited. To compensate, the astronauts will require vitamin D supplements.²⁴

Movie 3.1 Radiation and Cell Damage



²⁴ http://www.nasa.gov/vision/space/travelinginspace/keeping_astronauts_healthy_prt.htm

Chapter 4

Applications to Life on Earth: Radiation as a Tool



Applications to Life on Earth: Radiation as a Tool

Applications to Life on Earth: Radiation as a Tool

Now that we have an understanding of radiation, its biological effects, and radiation countermeasures, it is important to learn about the beneficial uses of radiation. In this section, we will discuss examples of how ionizing radiation is used at clinics and hospitals to diagnose disease and injury, and summarize several radiation and radioactive isotope applications.

The Discovery of X-rays

Wilhelm Conrad Röntgen is chiefly associated with his discovery of X-rays. In 1895, Röntgen was carrying out experiments with a cathode ray electron generator (a sealed glass vacuum tube). He shielded the glowing tube with thick cardboard and was surprised to notice that sensitized paper at some distance



Figure 4.1: An early X-ray image.

from the tube would still glow – evidently as a result of radiation from the generator. Röntgen placed his hand between the generator and the coated paper on the wall and was astonished to observe that the shadow of the bones in his hand had projected on the paper as well! He repeated this experiment and created a “röntgenogram” of his wife’s hand – the first ever X-ray image on film. For this work, Röntgen was awarded the first Nobel Prize in Physics in 1901. To this day, radiographs (X-ray images of a patient’s body) are essential tools in the treatment of disease and injury.

Fluoroscopy

For certain kinds of health conditions, simple radiographs may not be sufficient. When real time observation or medical interventions are required, fluoroscopy is commonly used. Although it exposes a patient to a much higher dose of radiation than a conventional X-ray,



Figure 4.2: A fluoroscope.

fluoroscopy allows a doctor to observe an X-ray image of a patient's body in real time. This technique enables doctors to observe surgical procedures like an angioplasty, heart by-pass grafting, and coronary angiography (an X-ray examination of chambers, blood vessels, and blood flow in the heart). It also allows for real-time study of gastrointestinal processes.

CT Scanners

Another technique that is based on X-rays technology is computed axial tomography, also known as CT or CAT Scan. Interestingly, the data imaging techniques previously used on the spacecraft Mariner 4, which flew by Mars in 1964, eventually led to medical applications in CAT scans, diagnostic radiography, brain and cardiac angiography and ultrasound technologies.²⁵ CT

scanners use X-ray equipment to gather X-ray images from different angles around the body in spirals or slices. Computers are then used to assemble the images for a three-dimensional visualization of the patient's internal anatomy. The dose received during one CT Scan is approximately the same as 100 or more chest x-rays equivalents. The same image



Figure 4.3: A CAT Scan image of a human head.



Figure 4.4: The Siemens Symbia SPECT/CT scanner. Image Credit: Impact Scan.

processing technology has evolved and is used for applications like crop forecasting, planetary surface characterization, mapmaking, water evaluation, and disaster management.

Nuclear Medicine

Since the discovery of X-rays, scientists and doctors have worked together to develop tools that allow for imaging of internal anatomy and soft tissues. In nuclear medicine, doctors use a variety of imaging tools with radioactive substances to image a patient's internal anatomy and function. This is accomplished by introducing radioactive elements (radioisotopes) into the body of a patient by injection, inhalation, ingestion, or topical application.

²⁵ http://www.jpl.nasa.gov/history/index_beginnings.htm

Different radioisotopes then preferentially concentrate in certain organs. For example, radioactive iodine-131 collects in the thyroid gland (see Figure 4.5). As each radioisotope decays, it gives off radiation (such as gamma rays), which are now observed by a gamma ray detector. Variations in radiation

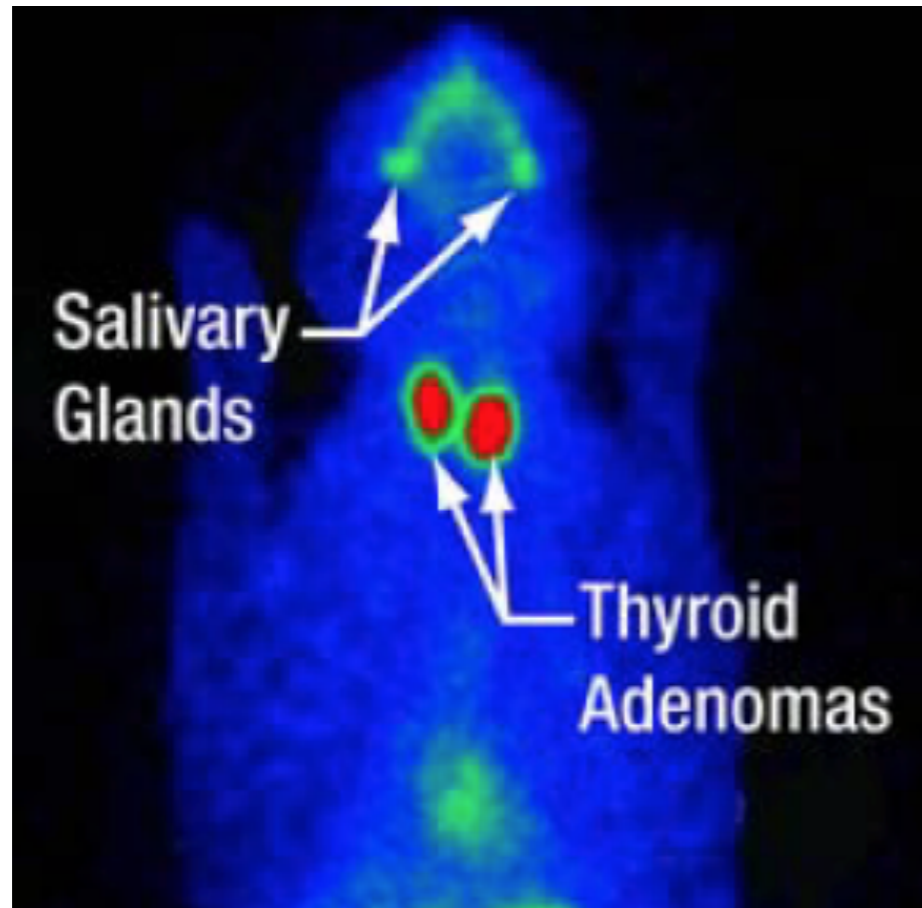


Figure 4.5: In this SPECT scintigram, the radioisotope has selectively concentrated at abnormal areas in the thyroid of a cat.

intensity in the body will activate film or a detector array to create an image. Typically, the radioisotopes usually have relatively short half-lives and decay rapidly, which helps to minimize the exposure to damaging radiation. In general, total doses are very low.

Two examples of high-powered imaging tools in nuclear medicine that use the tomographic approach are the Single Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET) Scanners. These instruments are especially suited to monitoring dynamic processes like cell metabolism or blood flow in the heart and lungs. Both use a gamma ray detector to measure gamma ray photons emitted from the radioisotopes used in the body. In each slice of Figure 4.6, PET images reveal changes in blood flow that are correlated with epilepsy in the right side of a patient's brain. SPECT technology is commonly used in brain scans but it can also be used to observe other organs such as the heart. The image that is acquired with a gamma camera or

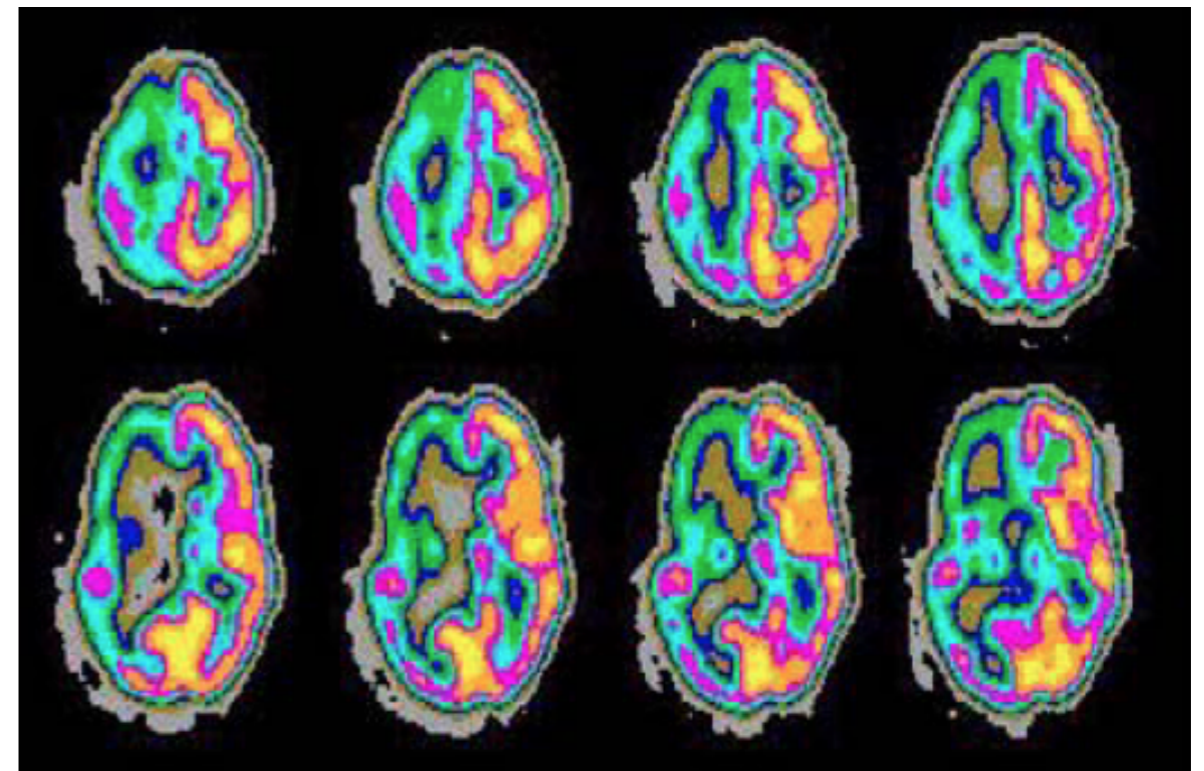


Figure 4.6: A PET image of an epilepsy patient.

SPECT is called a scintigram. Figure 4.7 and 4.8 show how SPECT imagery can be useful in visualizing along each axis of the heart and brain to compare its internal structure and function.

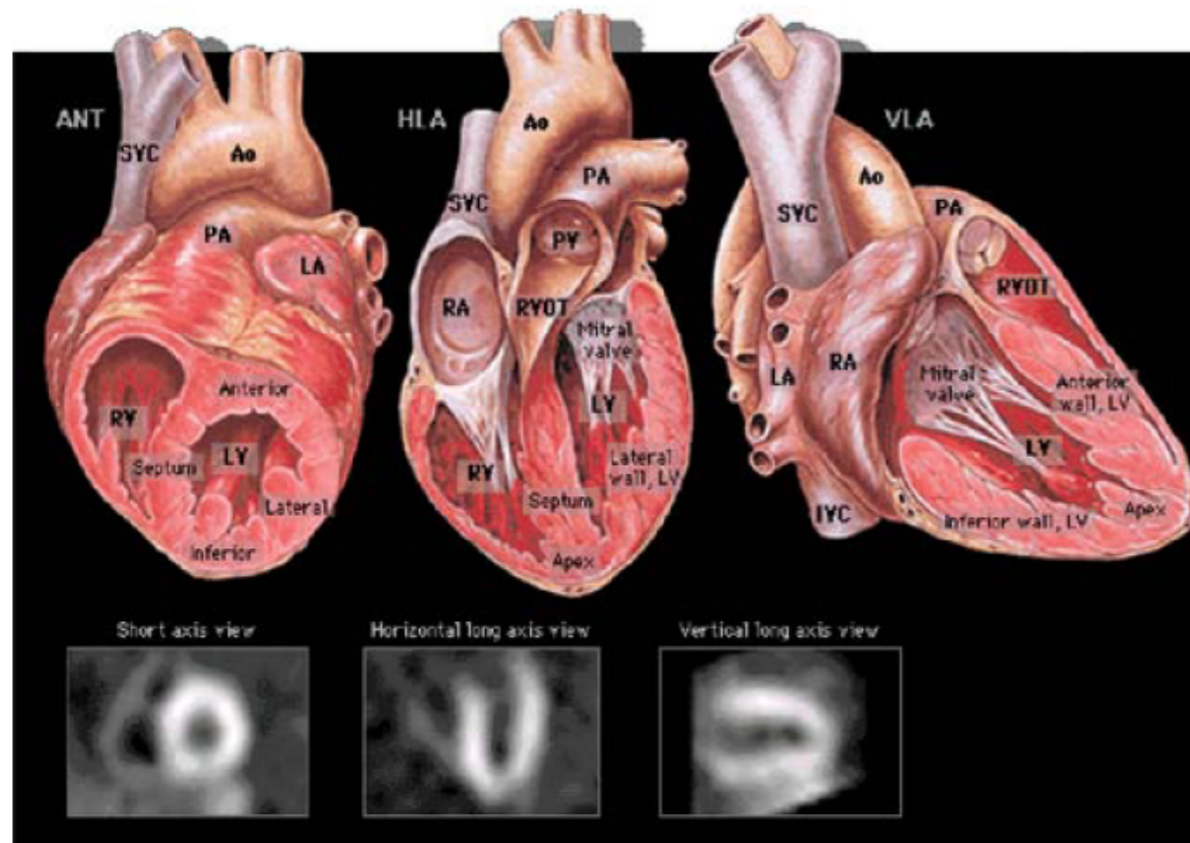


Figure 4.7: In this nuclear myocardial perfusion tomogram, the SPECT images are compared with drawings that are similar in cross sectional view. Image Credit: Yale School of Medicine.

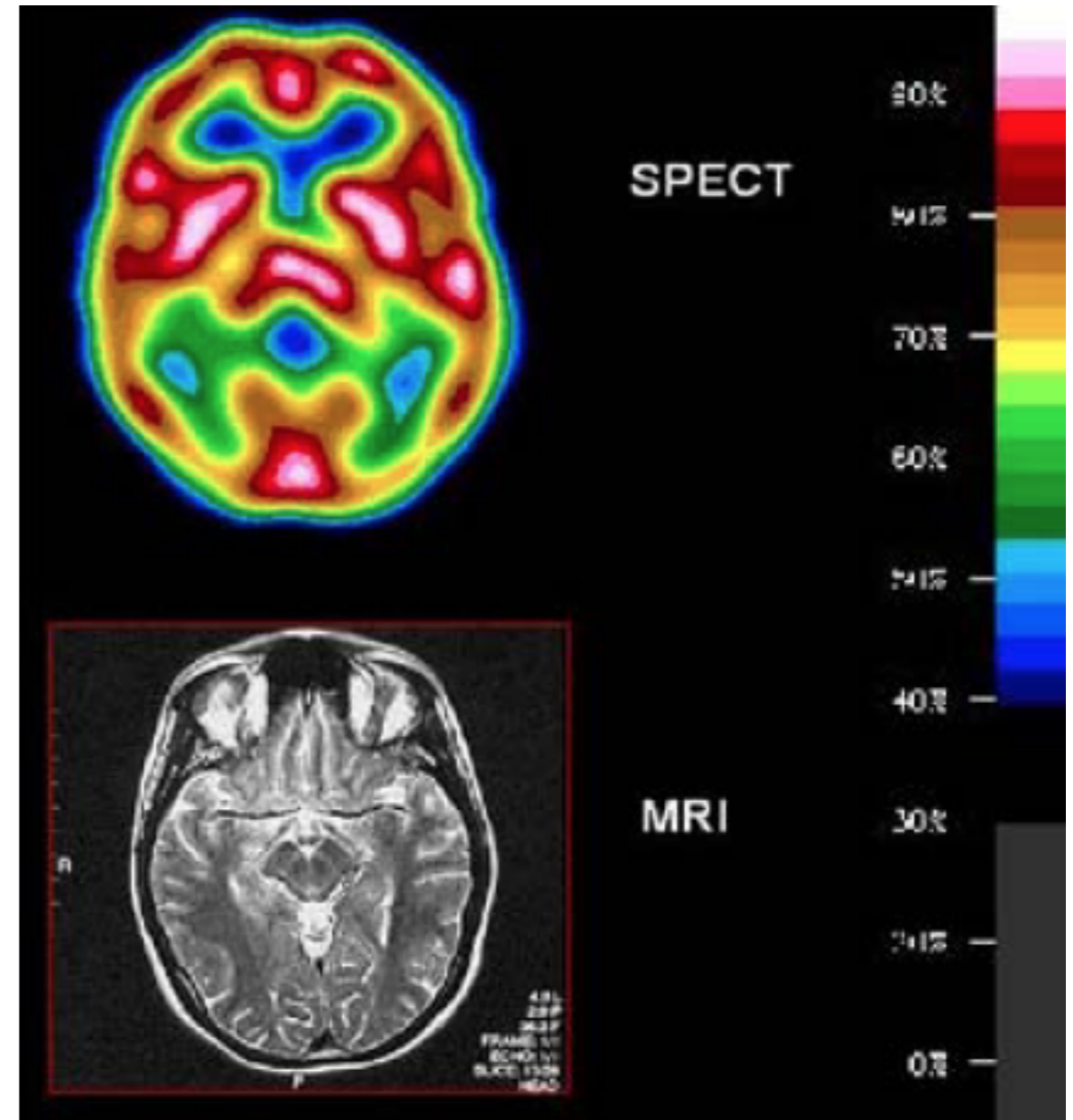


Figure 4.8: In this normal brain, SPECT and MRI transverse images can be used to compare structure and function. Image Credit: Dr. Robert Kohn

Magnetic Resonance Imaging

Not all medical imaging tools use ionizing radiation such as X-rays or gamma rays.

Magnetic Resonance Imaging (MRI) scans instead use low energy radio waves and strong magnetic fields to excite magnetic resonance in tissue atoms. MRI scans are commonly used to differentiate



Figure 4.9: An MRI scanner.

subtle differences within soft tissue regions of the body (differences in concentrations of water and fat give rise to different MRI signals in these regions). As in CT scan, all or part of the patient's body is placed inside a large cylinder during the MRI. A strong magnetic field is applied, which causes some of the molecules in the patient to align themselves along the direction of the field. This causes the hydrogen-containing compounds within the body to resonate at radio-frequency signals, which are picked up by a detector. A computer converts it to an image, which can be color-coded. In some cases, it is useful to combine MRI imagery with SPECT scintigrams to compare anatomical structures with their function (see Figure 4.8). Practically, using MRI for medical procedures does not add any radiation exposure to a person; however, it takes much longer to do than a CT to obtain the needed important medical images.

Radiation Therapy

When surgery alone cannot entirely remove a cancerous tumor, radiation therapy is sometimes used in conjunction with the surgery. Intraoperative radiation therapy (IORT) delivers a high dose of radiation to cancerous tumors while they are exposed during surgery.



Figure 4.10: Radiation therapy uses radiation to treat disease. Image Credit: Mayo Clinic.

Other techniques like three-dimensional conformal radiation therapy (3-D CRT) use radiation only. In 3-D CRT (also known as gamma-knife surgery), computers with specialized software use the information from CT Scans or MRIs to create beams of radiation that conform to the shape of a tumor. Once the exact location, size, and shape of the tumor is known, the computer instructs the linear accelerator to bombard the tumor with the conformal radiation. This technique is particularly useful in treating prostate cancer, lung cancer and certain brain tumors. Another example of conformal radiation therapy is Intensity-Modulated Radiation Therapy (IMRT), which precisely varies the intensity of the radiation beams used during treatment. Greater radiation intensity is directed at larger areas of the tumor, while weaker beams are directed to smaller areas of the tumor. This

helps to reduce the amount of radiation used and potentially limits the amount of radiation exposure to healthy tissue. In some cases, radiation is also combined with heat in treatments to kill cancer.

Brachytherapy

In each of the previously discussed examples, radiation delivered from a source external to the patient's body. However, there are internal forms of radiation therapy like Brachytherapy, which is designed to deliver a high dose radiation from inside the body. Brachytherapy involves placing a protected source of radiation (such as Iridium-192 or Cesium-131 that has been encased in tubes, wires, or capsules, see figure 4.11) directly within the tumor or very near to it.



Figure 4.11: Tiny capsules filled with Cesium-131 are implanted in or near a tumor. X-rays emitted by the cesium kill the cancer cells. Image Credit: Pacific Northwest National Lab.

Side Effects of Radiation Therapy

Exposure to radiation can cause negative side effects, ranging from dry mouth, difficulty swallowing, changes in taste, nausea, vomiting, diarrhea, irritated skin, hair loss, chest tightness, cough,

shortness of breath, fatigue, or ear aches. In addition, physiological complications like bone marrow suppression may result. This can cause anemia, low white blood cell count, and low platelet count. Secondary malignancies or treatment-associated cancers can sometimes occur in patients years after radiation therapy. Some brain tumor patients experience damage to healthy tissues that leads to cognitive impairment, or the loss of the ability to remember, learn, and complete certain tasks. As a result, a great deal of research focuses on maximizing the benefits of tumor killing radiation while minimizing its effects on healthy tissue surrounding the tumor. It is important to note that the location and intensity of radiation exposure affects the nature of negative side effects.

Biotechnological and Chemical Uses

There is a great deal of ongoing biochemical research that uses radiation sources. Much of this work investigates the molecular mechanisms responsible for biological processes. For example, scientists use high-intensity X-ray beams in crystallography to produce images of the crystal structures²⁶ of biochemicals such as the flavin-containing monooxygenase seen in Figure 4.12. By studying the crystal structure of biochemicals, scientists are able to create step-by-step snapshots of chemicals at different stages of catalytic action. Crystallography is also used to create three-dimensional structures of particular proteins with the purpose of

²⁶ http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=06-76

designing drugs that interact specifically with these proteins. Other researchers use radioactive isotopes in chemistry labs to track the path a chemical follows during a chemical reaction. To accomplish this, radioactive isotopes are incorporated into reactants, the chemicals are mixed, and the reaction is carefully monitored over time. This procedure is particularly useful for tracing underground rivers, following blood supply to a brain tumor, visualizing brain function itself, or the development of an embryo.

$$t = \frac{1}{\lambda} \ln \left(1 + \frac{D}{P} \right)$$

Where t is the age of the rock or mineral specimen,
 D is the number of atoms of a daughter product today,
 P is the number of atoms of the parent isotope today,
 \ln is the natural logarithm (logarithm to base e), and,
 λ is the appropriate decay constant.

The decay constant for each parent isotope is related to its half-life,

$t^{1/2}$ by the following expression: $t^{1/2} = \frac{\ln 2}{\lambda}$

Figure 4.12: The half-life of naturally occurring radioactive substances in a sample can be used to determine the age of the sample.
 Image Credit: USGS.

27 <http://pubs.usgs.gov/gip/geotime/radiometric.html>

28 <http://pubs.usgs.gov/gip/geotime/radiometric.html>

Radiometric Dating

Radiometric dating is a technique used to date both physical and biological matter. It is based on knowing the decay rates of naturally occurring isotopes. Radioactive decay is a spontaneous process in which an unstable atom emits particles (electrons or much heavier alpha particles—helium nuclei) from its nucleus to create a different form (an isotope) of the same element. The rate of decay is expressed in terms of an isotope’s half-life, or the time it takes for one-half of the radioactive isotope in a sample to decay. Many radioactive isotopes have rapid rates of decay (short half-lives) and lose their radioactivity within a few days or years. Some isotopes decay much more slowly over millions or billions of years, and serve scientists as “geologic clocks.”²⁷ Geologists can determine the age of a geologic formation or fossil by using a mathematical formula in

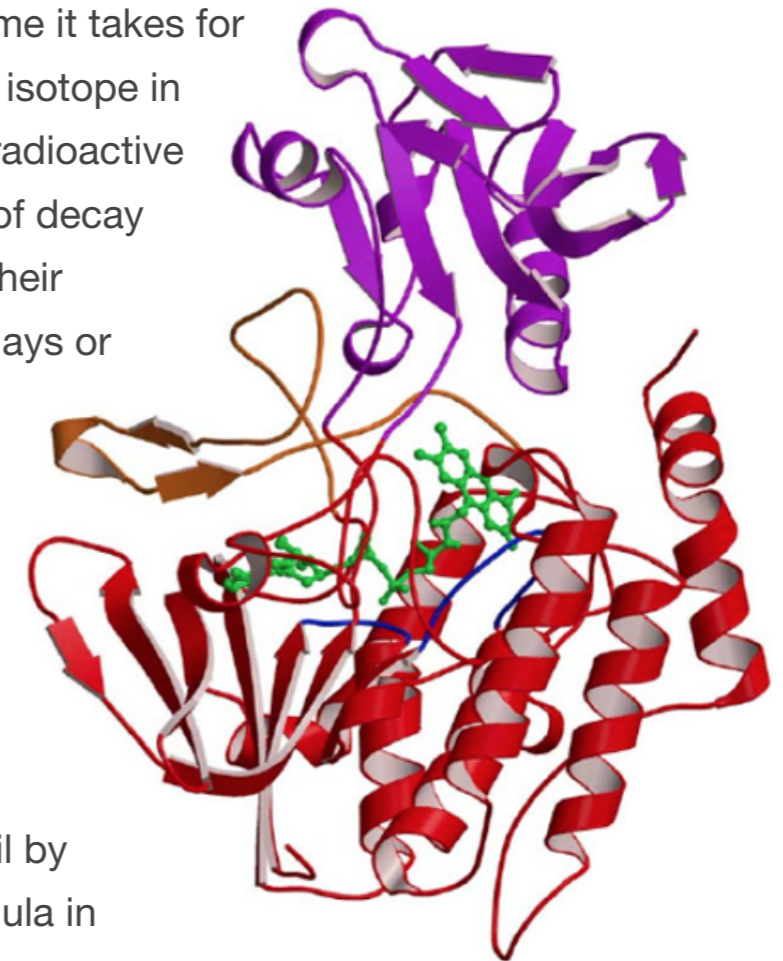


Figure 4.13: Radiation can be used to learn about the shape of enzymes. Image Credit: Brookhaven National

Figure 4.12.²⁸

Consumer Products

Many common consumer products are manufactured with, or naturally contain, radioactive material. Examples include smoke detectors, watches, clocks, ceramics, glass, camera lenses, fertilizers, and gas lantern mantles. Foods that have a low sodium salt substitute may contain potassium-40. In the 1920s, some products were sold as radium-containing “cure-alls!”

Power Sources

Heat produced from the decay of radioactive substances can be used to generate electricity by means of radioisotope thermoelectric generators (RTGs). The Pioneer, Viking, Voyager, Galileo, Ulysses, and Cassini (Figure 4.14)²⁹ spacecrafts all used this technology. On larger scales, electrical energy can also be produced through fission of radioactive materials like Uranium 238.

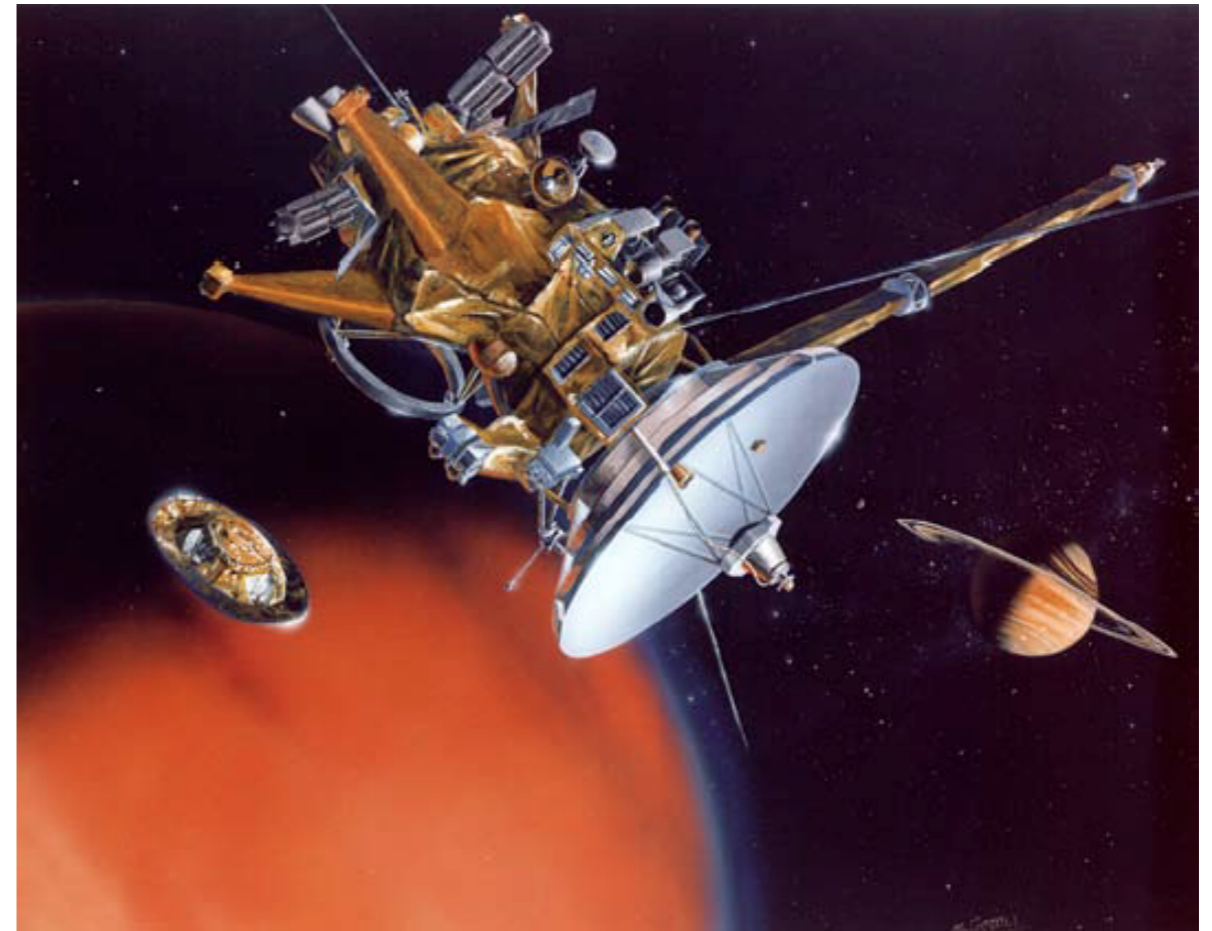
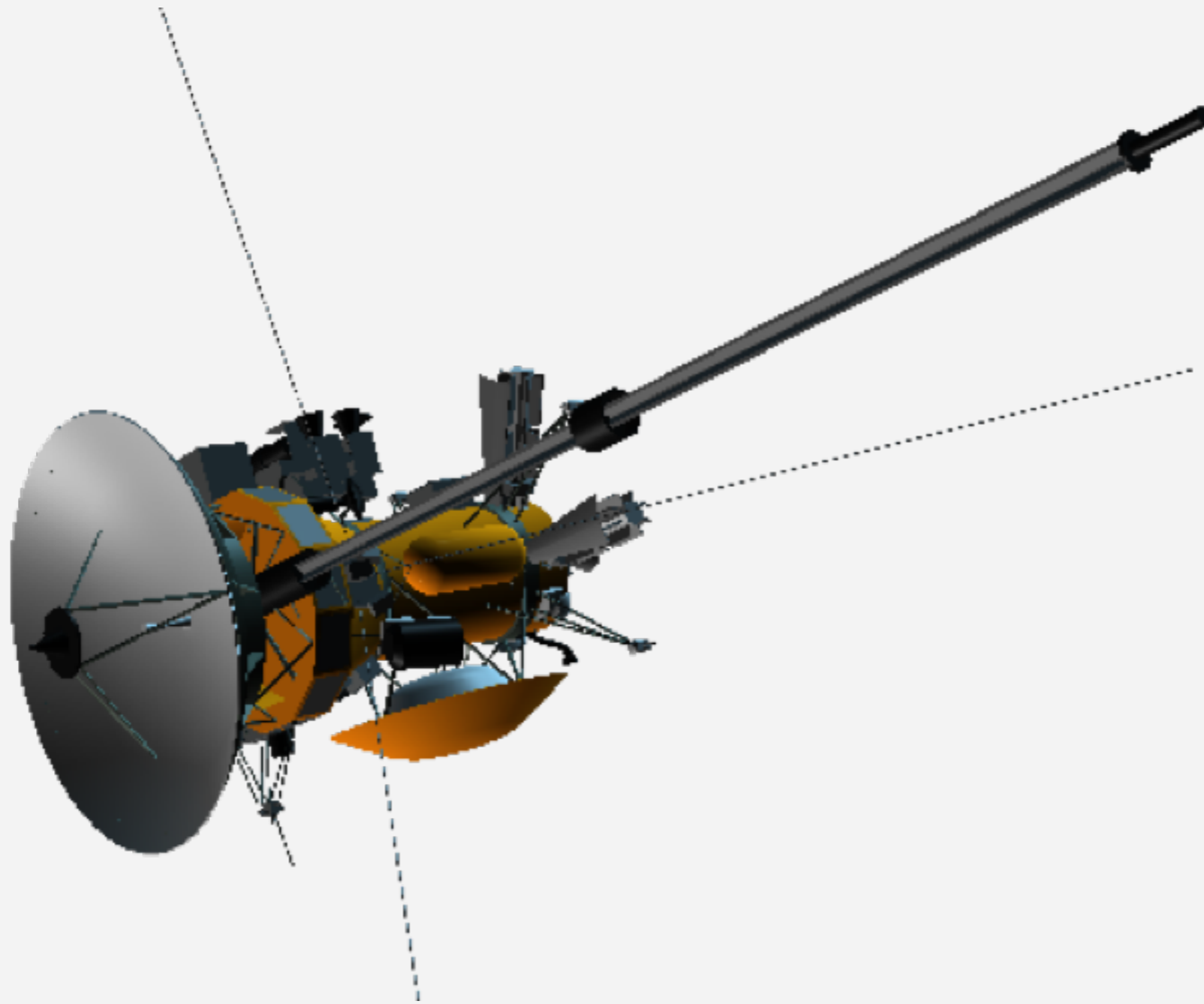


Figure 4.14: The Cassini spacecraft.

²⁹ <http://solarsystem.nasa.gov/multimedia/gallery.cfm?Category=Spacecraft&Page=15>

Interactive 4.1 Cassini Spacecraft Model



Drag image to rotate - Pinch to expand and contract image - Double tap center to reset view

Sterilization and Food Irradiation

In biology or tissue culture laboratories, UV radiation is an essential part of everyday operations in facilities that require sterile conditions during cell plating, tissue handling, or specimen transfer. Prior to sensitive operations, UV radiation is used to sterilize surfaces to ensure clean working conditions before the operations begin. Notice the bright blue light in the picture in Figure 4.15. It is a UV light inside a laminar flow hood. When it is turned on, the internal work volume of the hood is being sterilized.

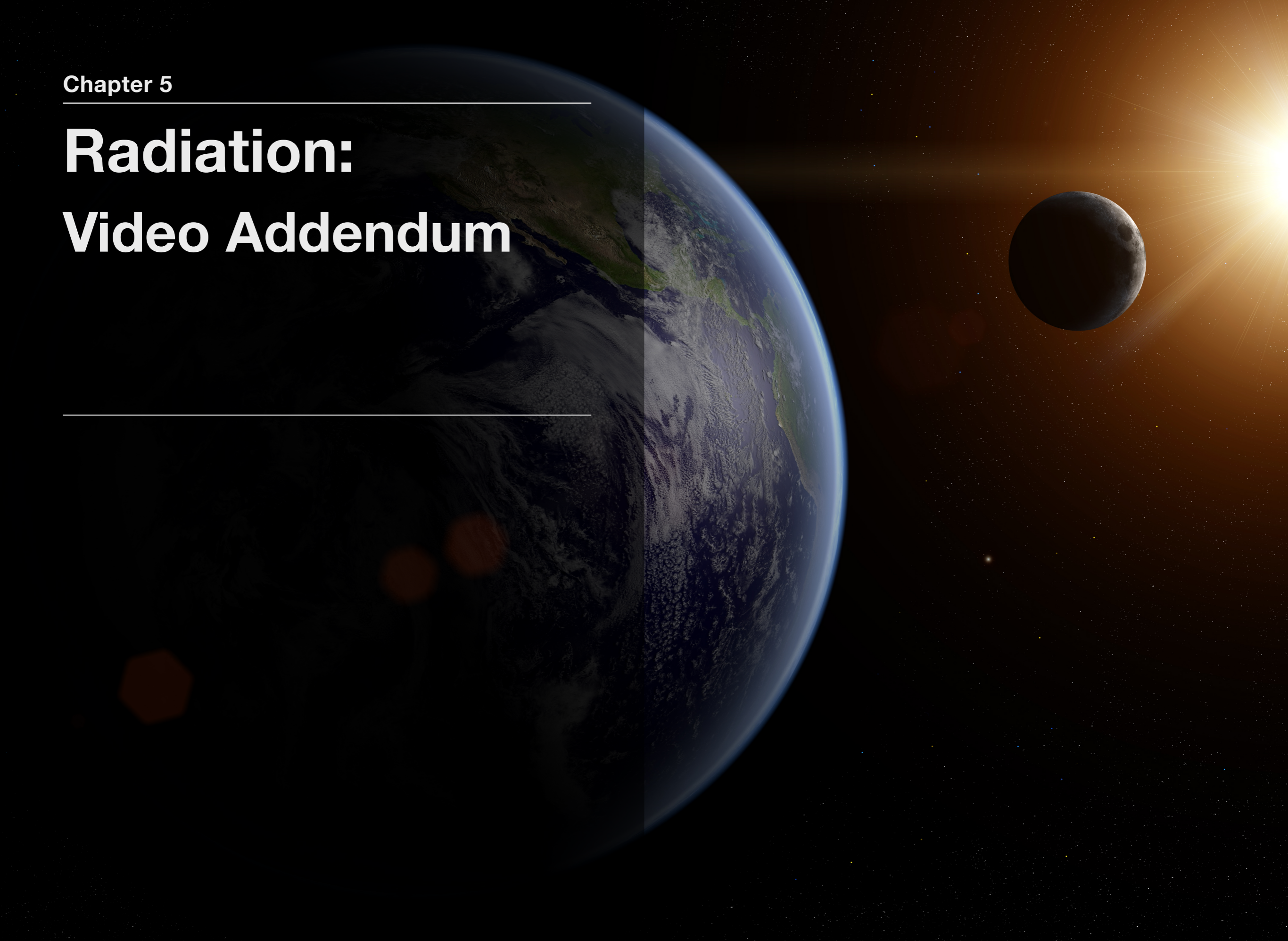
One method of preserving fresh or packaged food is to expose it to ionizing radiation, which is a process known as cold pasteurization. This process kills any microbes that could cause spoilage or disease to the consumer. Food sterilization by radiation is the most studied food preservation process and has been shown to be safe and reliable.



Figure 4.15: UV lights inside a laminar flow hood at NASA Ames.

Chapter 5

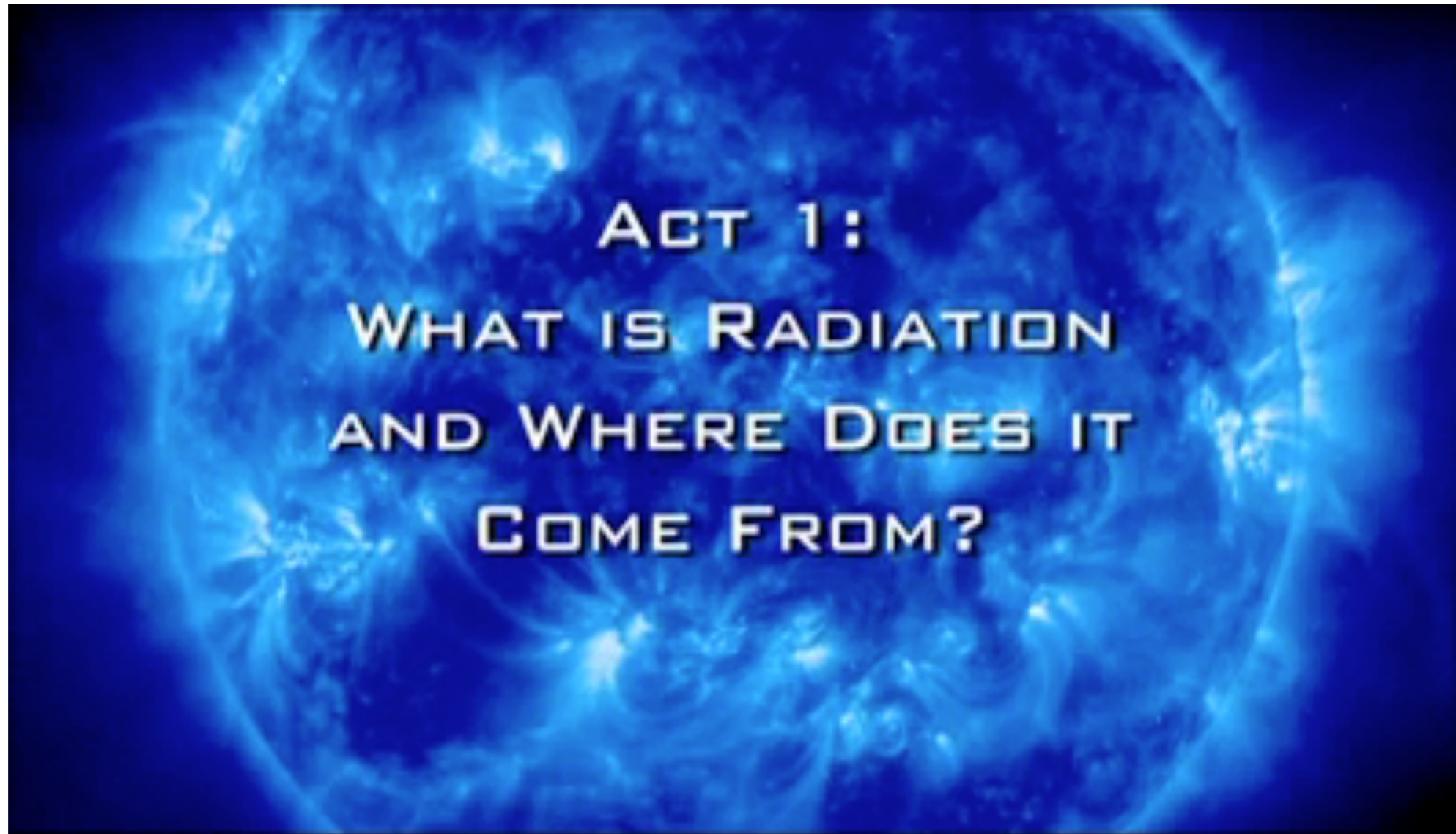
Radiation: Video Addendum



Movie 5.1 Solar Dynamics Observatory (SDO) Teaser



Movie 5.2 Act 1: What is Radiation and Where Does It Come From?



From NASA's Space Fairing Challenge

Movie 5.3 Act 2: Space Radiation and Human Health



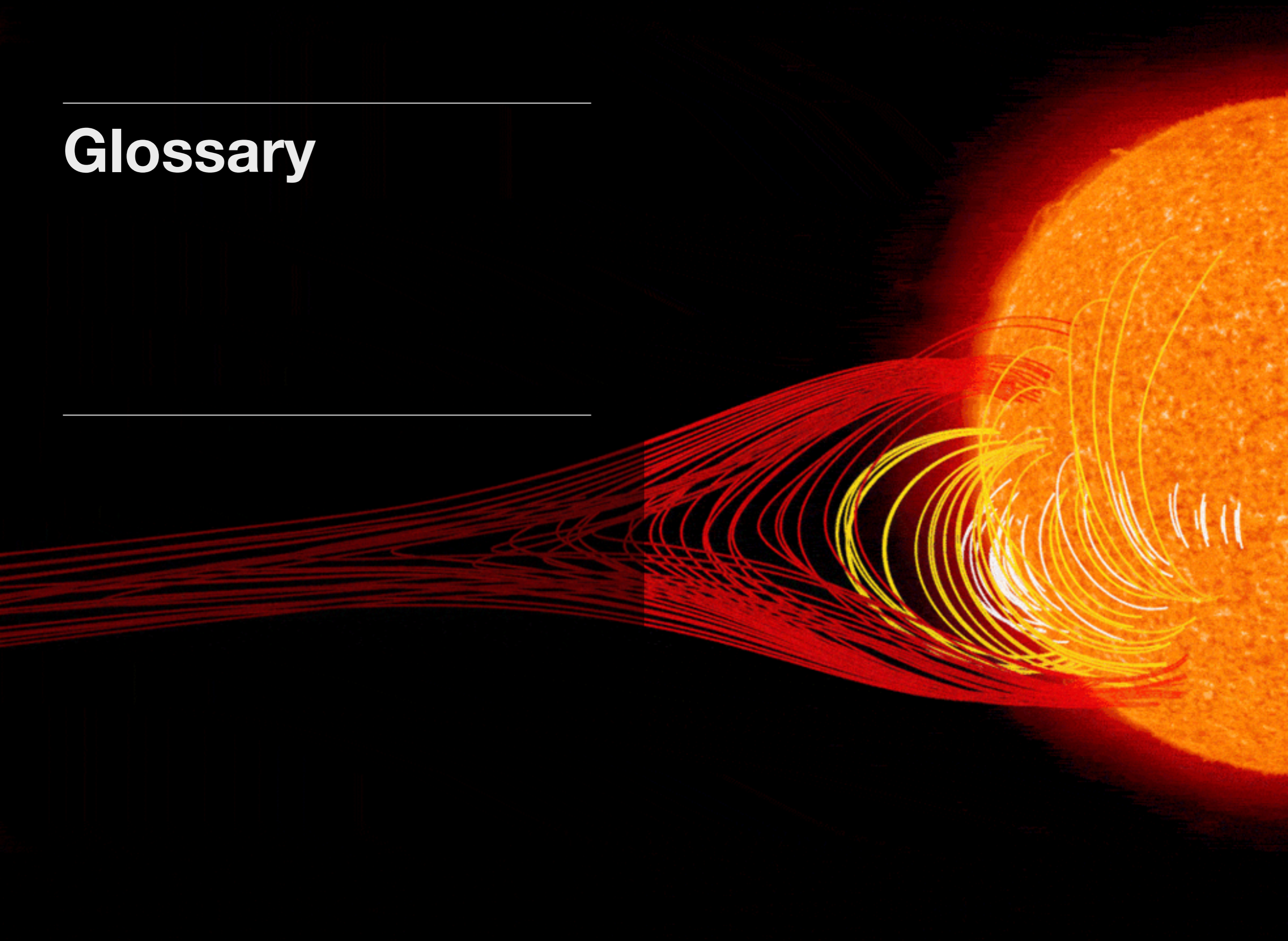
From NASA's Space Fairing Challenge

Movie 5.4 Act 3: Protection from Space Radiation



From NASA's Space Fairing Challenge

Glossary



Glossary

Acute exposure is short-term, high-level exposure to radiation. The effects of acute radiation exposure become more severe as the exposure increases. Health effects from acute exposure to radiation usually appear quickly. The physical response is called radiation sickness, or radiation poisoning.

The **Central Nervous System (CNS)** is the brain and the spinal cord. You use this system to think and to take action. The CNS helps to coordinate muscle and organ activity, and monitor input from your senses.

Chronic exposure is long-term, low-level exposure to radiation. Higher levels of radiation exposure make these health effects more likely to occur, but do not influence the type or severity of the effect. Examples of health effects from chronic radiation damage include cancer, leukemia, and genetic changes.

Chromosomes are the forms in which genetic information, DNA (deoxyribonucleic acid), are packaged in our cells. Human cells contain 23 pairs of chromosomes. Each chromosome contains a single long thread of DNA, wrapped around proteins that help keep the DNA organized within the cell. The blueprint for life (as we know it) is contained within DNA.

Coronal Mass Ejections (CME) are explosions that occur on the surface of the Sun. These eruptions release massive amounts of

energy out into space in the form of X-rays, gamma rays, and streams of protons and electrons called solar particle events. CME can be very harmful to space explorers.

DNA (deoxyribonucleic acid) is the molecule that encodes genetic information in cells. DNA consists of two strands of alternating phosphate and deoxyribose sugar molecules zipped together by pairs of nucleotide bases. The four nucleotides in DNA contain the bases adenine (A), guanine (G), cytosine (C), and thymine (T). In nature, base pairs form only between A and T and between G and C; thus the base sequence of each single strand can be deduced from that of its partner.

Galactic Cosmic Radiation (GCR) are charged particles moving at nearly the speed of light. They can cause damage as they pass through matter and generally pass unimpeded through a typical spacecraft or the skin of an astronaut. GCR consists mostly of protons (nuclei of hydrogen atoms), some alpha particles (helium nuclei), and lesser amounts of nuclei of carbon, nitrogen, oxygen, and heavier atoms. During solar maximum, GCR passing through our solar system is deflected (lessened) because changes in the Sun's magnetic field due to solar flares and coronal mass ejections. GCR can be very harmful to space explorers.

Hematopoietic syndrome refers to the symptoms caused by the effects of radiation on blood producing organs (spleen, lymph nodes, and bone marrow). Damage to these organs can cause a shortage of white blood cells, red blood cells, and platelets,

which can lead to anemia, bleeding, fatigue, weakness, and infections.

Prodromic syndrome refers to the initial symptoms (nausea, vomiting, and diarrhea) that indicate radiation poisoning.

Solar Cycle is the 11-year cycle of the Sun. During this period, the Sun varies in activity, producing large numbers of sunspots at solar maximum, and few during solar minimum. Solar maximum returns approximately every 11 years.

Solar Maximum is the period of greatest solar activity during the Sun's 11-year solar cycle. During solar maximum, the Sun is highly active and has many sunspots. Its magnetic field is more able to effectively shield the inner solar system from galactic cosmic radiation, but numerous solar flares and coronal mass ejections with harmful particle radiation are common.

Solar Minimum is the period of least solar activity during the Sun's 11-year solar cycle. During solar minimum, the Sun is relatively inactive and has few sunspots. Its magnetic field is unable to effectively shield the inner solar system from galactic cosmic radiation. Solar flares and coronal mass ejections are rare or absent.

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Related Glossary Terms

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Find Term

Central Nervous System (CNS)

The **Central Nervous System (CNS)** is the brain and the spinal cord. You use this system to think and to take action. The CNS helps to coordinate muscle and organ activity, and monitor input from your senses.

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Drag related terms here

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Drag related terms here

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Solar Minimum

Solar Minimum is the period of least solar activity during the Sun's 11-year solar cycle. During solar minimum, the Sun is relatively inactive and has few sunspots. Its magnetic field is unable to effectively shield the inner solar system from galactic cosmic radiation. Solar flares and coronal mass ejections are rare or absent.

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