Space Environments

Introduction
Kamlesh Lulla

Orbital Debris
Eric Christiansen
Kamlesh Lulla

Space Radiation and Space Weather
Steve Johnson
Neal Zapp
Kamlesh Lulla

Where does "space" really begin?

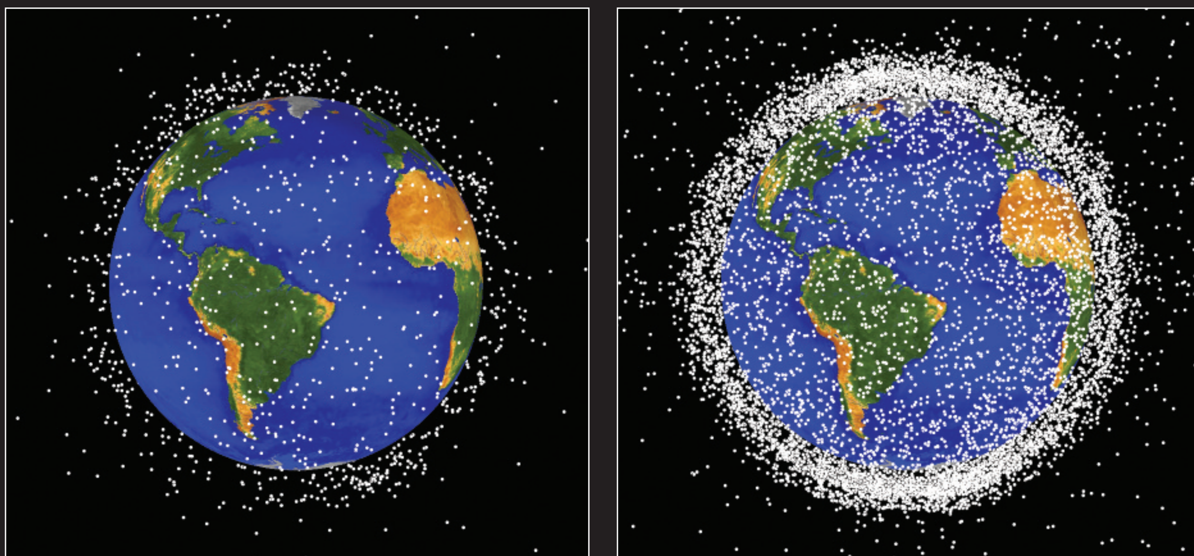
The Earth's atmosphere begins to thin out as we ascend to higher altitudes. This thinning continues in the near-space environment. International aeronautics standards use the altitude of 100 km (62 miles) to mark the beginning of the space environment and the end of Earth's atmosphere. The Space Shuttle was flown at various altitudes from 185 to 593 km (100 to 320 nautical miles) during the Hubble Space Telescope missions, but it generally flew at an altitude of around 306 km (165 nautical miles) in what is commonly called low-Earth orbit.

What is environment like in space? Travel in space environment exposes vehicles and their occupants to: vacuum-like conditions, very low or zero gravity, high solar illumination levels, cosmic rays or radiation, natural micrometeoroid particles or fragments, and human-made debris—called "orbital debris"—from space missions. Thus, the space environment posed distinct challenges for both the shuttle flight crew and hardware.

You may be surprised to learn that, on average, one human-made object falls back to Earth from space each day. The good news is that most objects are small fragments that usually burn up as they reenter Earth's atmosphere. Those that survive re-entry likely land in water or in large, sparsely populated regions such as the Australian Outback or the Canadian Tundra. Of course, not all objects fall to Earth. Thousands remain in orbit for a considerable duration, giving rise to a population of "space junk" or "debris" that affected the shuttle and its operations.

Space radiation is also an inseparable component of the space environment. Radiation exposure is unavoidable and it affects space travelers, hardware, and operations. NASA conducted operations and experiments on the shuttle to characterize the radiation environment, document astronaut exposures, and find ways to minimize this exposure to protect both the humans and the hardware.

What Goes Up in Space May Not Always Return to Earth



Growth of orbital debris: Each dot represents a debris object that is greater than 10 cm (4 in.) in diameter and has been cataloged. Comparison of 1970 (left) and 2010 maps shows clear evidence of rapid growth in debris population over the past 40 years.

What is orbital debris?

You have probably heard of human-made "space junk" or "space debris pollution." Since the dawn of space activities initiated with the launch of Sputnik in 1957, many nations have launched satellites, probes, and spacecraft into space. Some of these objects have come back to Earth and burned up in the atmosphere on re-entry. Many others remained in orbit and disintegrated into pieces that circle the Earth at around 27,000 kph (17,000 mph) in low-Earth orbit. This is orbital debris. It can be as small as a flake of paint from a spacecraft or as large as a school bus, and can impact operational spacecraft at very high impact speeds (up to 55,000 kph [34,000 mph). This space junk is of concern to all spacefaring nations.

What is a micrometeoroid?

Micrometeoroids are common, small pieces or fragments of rock or metal in orbit about the sun. These fragments have origins in the solar system and were generated from asteroids or comets, or left over from the birth of the solar system (i.e., they are natural debris). Micrometeoroids could pose a significant threat to space missions. They can impact at a higher velocity than orbital debris, and even the tiniest pieces can significantly damage spacecraft.

How much orbital debris is present, and how is it monitored?

Experts report more than 21,000 pieces of debris larger than 10 cm (4 in.) in diameter in orbit around Earth. The number of debris particles between 1 cm (0.4 in.) and 10 cm (4 in.) in diameter is estimated to be around 500,000. Experts think the number of particles smaller than 1 cm (0.4 in.) in size exceeds tens of millions.

The US Space Surveillance Network tracks large orbital debris (>10 cm [4 in.]) routinely. It uses ground-based radars to observe objects as small as 3 mm (0.12 in.) and provides a basis for a statistical estimate of its numbers. Orbital debris 1 mm (0.04 in.) in diameter and smaller is determined by examining impact features on the surfaces of returned spacecraft, such as the Orbiter.

How has the debris grown?

Debris population in space has grown as more and more space missions are launched. So, what are we doing about orbital debris?

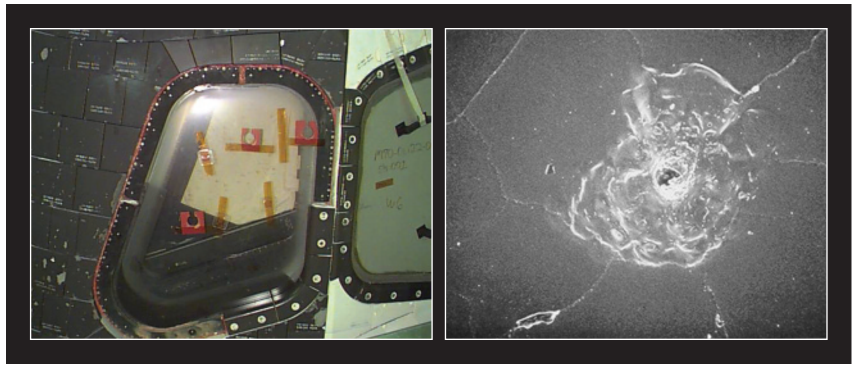
In 1995, NASA became the world's first space agency to develop a comprehensive set of guidelines for mitigation of orbital debris. Since then, other countries have joined in the effort. NASA is part of the Inter-Agency Space Debris Coordination Committee consisting of 10 nations and the European Space Agency whose purpose includes identifying cooperative activities to mitigate orbital debris. This includes stimulation for engineering/research based on solutions.

Orbital Debris

You have probably seen video clips of US Airways Flight 1549 glide into the Hudson River for landing in 2009 after a flock of geese disabled its engines. This incident highlighted the dangers of the local aviation environment on Earth. In space, while no geese posed a threat, fast-traveling debris consisting of fragments of spacecrafts or tiny pieces of meteoroids posed potential dangers to the shuttle.

Have you ever wondered what a postflight inspection of the Orbiter might have revealed? During postflight assessments, NASA engineers found over 1,000 hits caused by micrometeoroids and orbital debris that had occurred over the course of several years.

Why is it important to be concerned about human-made debris or natural meteoroid particles? The damages caused by debris impacts required shuttle windows to be replaced, wing leading edge to be repaired, and payload bay radiator panels and connector lines to be refurbished. Thus, the mitigation of such impacts became a high priority at NASA in its efforts to safeguard the spacecraft and astronaut crews and conduct mission operations without a glitch.



After each flight, the Orbiter was carefully examined for impact damage from high-speed orbital debris and meteoroids. Each of the shuttle windows were inspected with microscopes, which typically revealed several minor impacts (these images from STS-97, 2000). On average, one to two window panes were replaced after each mission due to these impacts or other contamination.

The large aluminum radiators attached to the inside of the cargo bay doors were examined for possible punctures (image on left from STS-115, 2006). Close-up inspections sometimes revealed complete penetrations of the radiator and debris from the impactor (magnified image on right from STS-90, 1998).

Was the Space Shuttle Damaged by Debris?

The shuttle was damaged by micrometeoroid and orbital debris, but the extent of damages varied with each flight. Postflight inspections revealed numerous debris impact damages requiring repairs to the vehicle. For example, NASA scrapped and replaced more than 100 windows, repaired hundreds of small sites on the radiator, and refurbished pits from impacts on the wing leading edge.

Notable Damage

The Space Transportation System (STS)-50 mission in 1992 spent nearly 10 days in a payload-bay-forward attitude (to reduce exposure to debris) during a 16-day mission. Postflight inspections revealed a crater measuring 0.57 mm (0.02 in.) in depth with a diameter of 7.2 mm (0.28 in.) by 6.8 mm (0.27 in.) in the right-hand forward window. The crater was caused by a piece of titanium-rich orbital debris. Because of the damage, the window had to be removed and replaced. The STS-50 mission experienced a large increase in payload bay door radiator impacts when compared to previous missions. The largest radiator impact on STS-50 occurred on the left-hand forward panel, producing a hole measuring 3.8 mm (0.15 in.) in diameter in the thermal control tape, and a hole measuring 1.1 mm (0.04 in.) in diameter in the face sheet. This impact was due to a piece of paint.

The 16-day STS-73 mission in 1995 carried a US Microgravity Module Spacelab module and an Extended Duration Orbiter cryogenics pallet in the payload bay. The vehicle was oriented with its port wing into the velocity vector for 13 days of the mission, and the port payload door was kept partially closed to protect the two payloads from debris impacts. Postflight inspections revealed a crater in the outside surface of the port payload bay door. The crater measured 17 mm (0.67 in.) in diameter and 6 mm (0.24 in.) deep. NASA found a 1.2-mm- (0.047 in.)-long fragment of a circuit board in the crater as well as many smaller pieces of circuit board and solder. Thus, a small piece of orbital debris (circuit board/solder) caused this particular impact damage.

After the STS-86 mission in 1997, NASA observed several significant debris impacts on the left-hand radiator interconnect lines. The aluminum tubes carried Freon® coolant between the Thermal Control System radiator panels. The largest impact, on the external line at a panel, penetrated just over halfway through the 0.9-mm- (0.035-in.)-thick coolant tube wall. A scanning electron microscope equipped with x-ray spectrometers examined samples of the damage. NASA decided the damage was likely due to impact by a small orbital debris particle composed of stainless steel. Additional inspections of the interior surface of the coolant tube wall determined that a small piece of the interior wall was removed directly opposite the impact crater on the exterior surface. This particular impact damage feature, called "detached spall," indicated that a complete penetration of the tube was about to happen. A tube leak would likely have resulted in a mission abort and possible loss of mission objectives.

After this mission, all external radiator lines on the Orbiter vehicles (flexible and hard lines) were toughened by installing a double-layer beta-cloth sleeve around the line. This sleeve was sewn together such that there was a gap between the two layers and a gap between the sleeve and coolant line that created a bumper-shield effect. Ground-based impact tests revealed that more effective protection from hypervelocity meteoroid and debris impacts could be obtained using several relatively thin layers (or "bumpers") that stood off from the item being protected.

Since the STS-86 mission, NASA has found more micrometeoroid and orbital debris impacts on the shuttle windows, radiators, and wing leading edge.

The Scientific Basis for Mitigating Orbital Debris Impact—How NASA Protected the Space Shuttle

NASA's active science and engineering program provided the agency with an understanding of orbital debris and its impact on the shuttle. Engineers implemented several techniques and changes to vehicle hardware design and operations to safeguard the shuttle from micrometeoroid and orbital debris impacts based on the scientific efforts discussed here.

NASA performed thousands of impact tests using high-velocity objects on representative samples of shuttle Thermal Protection System materials, extravehicular mobility unit materials, and other spacecraft components to determine impact parameters at the failure limits of the various subsystems. Engineers used test results to establish and improve "ballistic limit" equations that were programmed in the computer code tool used to calculate impact risks to specific Orbiter surfaces. NASA completed an integrated mission assessment with this code, including the effect of the different orientations the vehicle flew during a mission for varying amounts of time. This tool provided the basis for showing compliance of each shuttle mission to debris protection requirements.

Risk Assessment Using Mathematical Models

NASA, supported by these impact tests, used a computer code called BUMPER to assess micrometeoroid and orbital debris risk. The space agency used these risk assessments to evaluate methods to reduce risk, such as determining the best way to fly the shuttle to reduce debris damage and how much risk was reduced if areas of the shuttle were hardened or toughened from such impacts.

Design Modifications of Shuttle Components

NASA made several modifications to the shuttle to increase micrometeoroid and orbital debris protection, thereby improving crew safety and mission success.

The space agency improved the wing leading edge internal Thermal Protection System by adding Nextel™ insulation blankets that increased the thermal margins of the panel's structural attachment to the wing spar. This change allowed more damage to the wing leading edge panels before over-temperature conditions were reached on the critical structure behind those panels.

Another improvement involved toughening the radiator coolant flow tubes. This was accomplished by installing aluminum doublers over the coolant tubes in the payload bay door radiators. Additional protection to the flow loops was made in the form of adding a double-beta-cloth wrap that was attached via Velcro® around radiator panel-interconnect flexible and hard lines (0.63-cm [0.25-in.] gaps were sewn into the beta-cloth wraps to improve hypervelocity impact protection).

NASA added automatic isolation valves to each of the two thermal control flow loops on the vehicle to prevent excessive loss of coolant in the event of tube leak.

Operational Changes

Shuttle flight attitudes were identified (using BUMPER code) and flown whenever possible to reduce micrometeoroid and orbital debris risk. Impacts were quite directional. For the shuttle and the International Space Station (ISS), about 20 times more impacts would occur on the leading surfaces of the spacecraft (in the velocity direction) compared to the trailing surface and 200 times more impacts would occur on the leading surface compared to the Earth-facing surface (because the Earth provides shadowing). When the shuttle was docked to the ISS, the entire ISS-shuttle stack was yawed 180 degrees such that the ISS led and the shuttle trailed (i.e., the ISS was flying backward). This was done to protect sensitive surfaces on the belly of the shuttle from micrometeoroid and orbital debris impacts because the belly of the shuttle would be trailing when the ISS-shuttle stack completed the 180-degree yaw maneuver. The shuttle in free flight flew with tail forward and payload bay facing earthward whenever possible to again provide the greatest protection while conducting the mission.

An operational step to reduce micrometeoroid and orbital debris risk was made during the STS-73 mission, which flew predominately in a wing-forward, tail-to-Earth attitude. The Spacelab module, along with the Extended Duration Orbiter pallet containing high-pressure cryogenic oxygen and nitrogen, occupied the payload bay on this mission. To protect the payloads as well as reduce micrometeoroid and orbital debris risk to the radiators, the shuttle flew with the leading payload bay door nearly closed.

Another important step in reducing micrometeoroid and orbital debris risk for the shuttle was implemented with STS-114 (2005); this step included an inspection of vulnerable areas of the vehicle for damage. This inspection was performed late in the mission, just after undock from the ISS, using the Orbiter Boom Sensor System. The late inspection focused on the wing leading edge and nose cap of the Orbiter because those areas were relatively thin and sensitive to damage. If critical damage was found, the crew would perform a repair of the damage or would re-dock with the ISS and await a rescue mission to return to Earth.

On-orbit Damage Detection and Repair

With STS-114, NASA installed an on-orbit impact detection sensor system to detect impacts on the wing leading edge of the shuttle. The Wing Leading Edge Impact Detection System consisted of 132 single-axis accelerometers mounted along the length of the Orbiter's leading edge wing spars.

During launch, the accelerometers collected data at a rate of 20 kHz and stored these data on board for subsequent downlink to Mission Control. Within 6 to 8 hours of launch, summary files containing periodic subsamples of the data collected by each accelerometer were downlinked for analysis to find potential signatures of ascent damage. This analysis had to be completed within 24 to 48 hours of launch so the results could be used to schedule focused inspection using the Orbiter Boom Sensor System in orbit.

The Wing Leading Edge Impact Detection System was capable of detecting micrometeoroid and orbital debris impacts to the wing leading edge, although it was battery operated and did not continuously monitor for impacts. Rather, it was turned on during specific periods of the mission where the assessed risk was the highest.

Repair kits were developed to repair damages to the wing leading edge, nose cap, and Thermal Protection System tiles if damages didn't allow for safe return. Those repairs could be accomplished by the crew during an extravehicular activity.

Successfully Diminishing the Risk of Damage

Teams of NASA engineers and scientists worked diligently to enhance the safety of the Space Shuttle and the crew while in orbit by implementing threat mitigation techniques that included vehicle design change, on-orbit operational changes, and on-orbit detection and inspection. The design changes enhanced the survival ability of the wing leading edge and payload bay radiators.

Operational changes, such as flying low-risk flight attitudes, also improved crew safety and mission success. Inspection of high-risk areas

Kevin Chilton
General, US Air Force
United States Strategic Command/Joint Operations Command Center.
Pilot on STS-49 (1992) and STS-59 (1994).
Commander on STS-76 (1996).

The Need to Minimize Orbital Debris in Space

"Our Space Shuttle experiences gave us a deep appreciation and respect for the space environment—its vastness, its harshness, and its natural beauty. Hand in hand with this appreciation comes, in my view, a sense of stewardship for this domain we share, and will continue to share, with other countries and peoples. It's a realm over which no one has ownership, but for which all who traverse it are, in a sense, responsible.

"This imperative for responsibility became particularly poignant to me during one of my shuttle missions, when one day a crewmate noticed a disconcerting crack in the outer pane of the circular window on the side hatch. NASA scientists and engineers later determined the crack was caused by the high-speed impact of a miniscule piece of human-made debris. I'd prefer not to think what might have happened had it been something a bit larger. The event was a reminder to us that we were, in our fragile craft, mere travelers in a rather hazardous place of great velocities and hostile conditions. But, our collision with this other human-made object in space also made clear that we have a role in keeping the space environment as pristine as we can, and as we found it—if for nothing else, for the safety and freedom of space travels after ours.

"Later in my career, as Commander of U.S. Strategic Command, I saw this imperative for responsibility even more clearly in the aftermath of two significant debris-generating events: the January 2007 Chinese anti-satellite test, and the February 2009 collision between two satellites in low-Earth orbit. Both dramatically increased the debris count in low orbit and were wake-up calls for the imperative for more responsible behavior in the first case, and the need to better understand and to minimize—to the extent possible—the challenge of space debris in the latter. We've since taken steps to improve that understanding and to pursue debris mitigation, but there is still much more to be done.

"If we truly are to be good stewards of the space environment, we will need to make every reasonable effort to keep it habitable for both human and machine. This demands a deliberate effort to minimize orbital debris in the design, deployment, operation, and disposal of those spacecraft we send into orbit and beyond, as well as proactive efforts to mitigate the likelihood of spacecraft collisions with debris or other satellites in the future."

(e.g., wing leading edge and nose cap) along with repair were useful techniques pioneered by the Space Shuttle Program to further mitigate the risk of micrometeoroid and orbital debris impacts.

Summary

Experts estimate that, collectively, these implemented steps diminished the risk of damage from the orbital debris and micrometeoroids by a factor of 10 times or more.

Experience and knowledge gained from the shuttle orbital debris monitoring is valuable for current operations of the ISS and will have significant value as NASA develps future exploration concepts.

What Is Space Radiation?

Radiation may seem like a mystical, invisible force used in applications such as x-rays, nuclear power plants, and atomic bombs, and is the bread and butter of science fiction for creating mutant superheroes. The reality is that radiation is not so mysterious. Space radiation is composed of charged particles (90% protons) with high kinetic energies. Cellular damage results as a charged particle travels through the body, transferring its kinetic energy to the cellular molecules by stripping electrons and breaking molecular bonds.

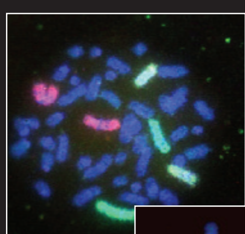
Deoxyribonucleic acid (DNA) bonds may be broken if a charged particle travels through the cell nucleus. In fact, scientists can observe chromosomal damage in the white blood cells (lymphocytes) in astronauts by comparing postflight chromosome damage to the preflight chromosome condition. If the chromosomes do not correctly rejoin in the aftermath, stable abnormal DNA combinations can create long-term health implications for astronauts. Accumulated cellular damage may lead to cancer, cataracts, or other health effects that can develop at any time in life after exposure.

There are three sources of space radiation: galactic cosmic radiation, trapped radiation, and solar energetic particle events. Galactic cosmic radiation is composed of atomic nuclei, with no attached electrons, traveling with high velocity and therefore significant kinetic energy. In fact, the highest energy particles are traveling near the speed of light (relativistic). High energy galactic cosmic radiation is impossible to shield with any reasonable shield thickness. Most importantly, of the three sources, galactic cosmic radiation creates the biggest risk to astronaut health. Trapped radiation—Van Allen belts—is composed of protons and electrons trapped in the magnetic field. Trapped proton energy is much lower than galactic cosmic radiation energy and is easier to shield. Solar energetic particle events are composed primarily of large numbers of energetic protons emitted from the sun over the course of 1 to 2 days. Solar energetic particle energies generally reside between trapped proton and galactic cosmic radiation.

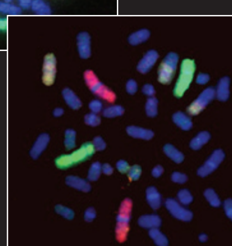
Radiation exposure in space is unavoidable and the potential for adverse health effects always remains. It is essential to understand the physics and biology of radiation interactions to measure and document astronaut exposures. It is equally important to conduct operations in such a way as to minimize crew exposures as much as practicable.

The Good, the Bad, and the Ugly

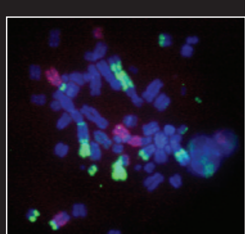
NASA is investigating a method of directly assessing the radiation risk by evaluating the amount of chromosome damage. Fluorescent chromosome painting techniques are used to paint Chromosome 1 (red), Chromosome 2 (green), and Chromosome 5 (yellow) in white blood cells to highlight rearrangement of DNA material.



The Good Normal cell reveals each of the three chromosome pairs are painted and intact.



The Bad One of the No. 5 chromosomes was damaged and mis-repaired. Cells with only a little damage may be worse because the cell survives and can pass the rearranged DNA code to subsequent cell generations.



The Ugly All three chromosome pairs have been damaged and rejoined in a complex manner. Though severely damaged, there is good news with the ugliness. Damaged DNA code will not be perpetuated because the cell is not likely to replicate.

The Eyes Have It!

Could astronauts be more susceptible to developing cataracts from space radiation?

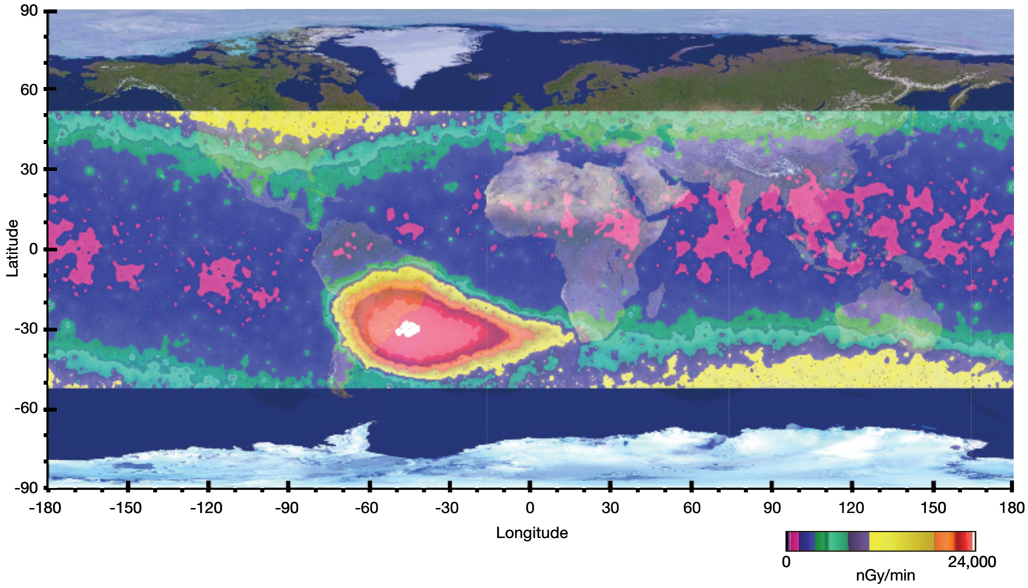
Researchers have recorded a higher-than-anticipated rate of cataracts in astronauts. Could the lens of the eye be more susceptible to developing cataracts from space radiation, especially as a result of exposure to biologically damaging heavy ion components of galactic cosmic radiation? Apollo astronauts were the first to report the effect known as "light flashes," which are generally attributed to heavy galactic cosmic radiation ions interacting within the eye. Astronauts on Skylab, shuttle, and the International Space Station have reported light flashes, but the reported frequency of flashes is greater during trajectories through higher latitudes in which radiation intensity is the highest.

Researchers used a pool of approximately 300 astronauts and divided them by their total mission doses. The "low-dose" group had exposures less than 800 mrem (8 mSv), and the "high-dose" group had greater exposures. The result: The high-dose group was more likely to develop cataracts than the low-dose group.

In addition, the astronauts were grouped by orbital inclination of their mission. The fraction of galactic cosmic radiation dose received by high-inclination missions (50 degrees) was greater than the galactic cosmic radiation dose fraction for low-inclination flights. This was due to the reduced magnetic shielding of radiation at higher latitudes encountered in trajectories of high-inclination flights; thus, these flights received more exposure to galactic cosmic radiation. This grouping allows for a comparison of astronauts with the same dose but with a different amount of exposure. As expected, the high-inclination group exhibited increased cataract incidence.

This research indicates that the risk of radiation-induced cataracts from heavy ion exposure is much higher than previously believed.

Radiation Intensity Inside the Shuttle



Radiation in low-Earth orbit is influenced by the magnetic field and follows a complex distribution pattern, as seen from measurements from STS-91 (1998). The prominent bull's-eye is a localized region of trapped radiation known as the South Atlantic Anomaly. The highest dose rates experienced by the shuttle occurred during transits through this region.

To manage the space radiation exposure risk to astronauts, NASA determined radiation exposure limits. Career exposure limits are established to limit the lifetime likelihood of adverse health effects from chronic exposure damage. Short-term exposure limits are established to ensure that astronauts do not receive acute exposures that might impair their ability to perform their duties.

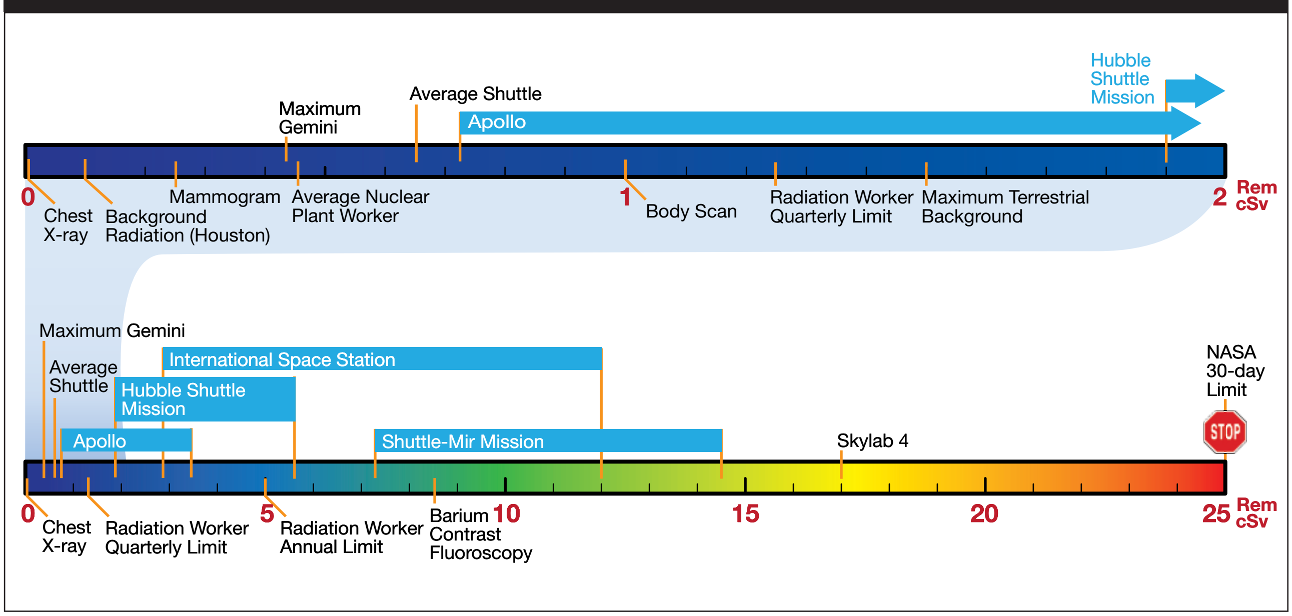
Using the Shuttle to Measure the Characteristics of Space Radiation

Scientists use two ways to measure radiation exposure to monitor astronaut health. The most frequent unit is the "dose" in units of rad or gray. Dose is solely a measure of the amount of energy deposited by the radiation. The second unit is "dose equivalent," which represents a level of biological effect of the radiation absorbed in the units of roentgen equivalents man (rem) or sievert (Sv). The amount of energy deposited by two different types of radiation may be the same, but the biological effect can differ vastly due to the damage density of different species of charged particles. A spectral weighting factor is used to adjust the dose into dose equivalent—the unit of interest when discussing astronaut exposures.

NASA developed an innovative instrument called the Tissue Equivalent Proportional Counter for experimentation on the shuttle to record the spectral distribution of measured radiation. Using the spectral information and the measured dose, an estimate of the dose equivalent could be made. Scientists used this instrument to conduct detailed assessments of the radiation environment surrounding the astronauts and their operational activities. Tissue Equivalent Proportional Counter measurements captured the dynamic changes in the radiation environment such as shift in locations and enhancements in trapped radiation. Far superior to the standard trapped radiation computer models, Tissue Equivalent Proportional Counter data became an effective tool for operational planning. Thus, mission planners were able to avoid additional exposure to the crew during extravehicular activities (EVAs).

Here is an example of why measurements are important: During a severe solar magnetic storm in March 1989, the electron population was enhanced by a factor of 50 relative to quiet conditions. Without these types of measurements, engineers would not have known about the belt enhancement and could not have considered this vital information in planning EVAs or evaluating astronaut radiation exposures.

Relative Radiation Exposure



Space Shuttle Experiments Advance the Science of Radiation Shielding

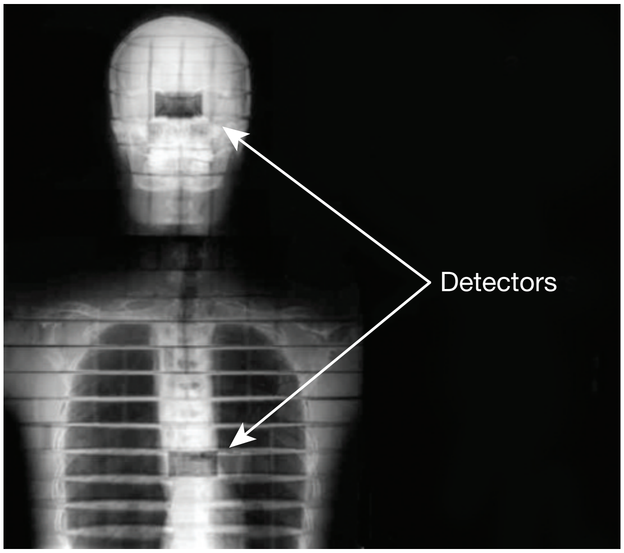
How do the characteristics of radiation change as it travels through shielding or the body? What is the relative exposure to the internal organs compared to external exposure measurements? Answers to these questions assist in evaluating astronaut exposure risks.

Space Shuttle experiments, flown twice, used a set of multiple Tissue Equivalent Proportional Counters with detectors located at the center of polyethylene and aluminum spheres of different thicknesses to evaluate radiation source and transport/penetration models.

In polyethylene measurements, the galactic cosmic radiation dose equivalent was reduced by 40% with 12 cm (4.7 in.) of water. (Water is the international standard for shielding. Effectiveness of shielding is compared to this standard.) In contrast, aluminum shielding reduced the galactic cosmic radiation dose equivalent by a negligible amount using twice the polyethylene shield weight. The aluminum was significantly less effective and much heavier. Measurements of trapped radiation achieved a 70% reduction with 12 cm (4.7 in.) of polyethylene but required 50% more aluminum weight to achieve the same level of protection. Thus, polyethylene is a much better shield than aluminum for space radiation. These results contributed to improving radiation shielding on the International Space Station (ISS).

Human Phantoms in Flight

The shuttle sphere shielding experiments were followed with an innovative way to measure radiation penetration. This innovation was called "body phantoms"—anthropomorphic density phantom (anatomical and tissue density) replicas of the human body. The first experiment used a head phantom; the second used a phantom torso along with the head phantom. The body phantom was constructed out of skeletal bones and tissue-equivalent plastics to simulate internal organs. The phantom torso was filled with 350 small holes, each containing multiple passive detectors. Five silicon detectors were placed at strategic organ sites.



The phantom torso—a body phantom without arms or legs—was constructed out of skeletal bones and tissue-equivalent plastics to simulate internal organs. This x-ray image shows two locations of detectors as examples of multiple passive detectors.

Surprisingly, the phantom torso experiment revealed that the radiation penetration within the body did not decrease with depth as much as the models would indicate. Scientists found that the dose at blood-forming organs—some of the most radiosensitive sites—was 80% of the skin dose. The dose equivalent was nearly the same as the skin. The higher measured internal dose levels inferred more risk to internal organs for a given level of external radiation exposure.

The shuttle phantom torso experiment also provided an opportunity to make measurements of the neutron levels within the body. Neutrons are created as secondary products within the spacecraft. How does this happen? As an example, an energetic proton could hit the nucleus of an aluminum atom, causing the aluminum atom to break into several pieces that probably include neutrons. Neutrons have the potential to pose more biological risk to astronauts than do most charged particles. Also, neutrons are difficult to measure in space because charged particles interfere by producing many of the same interactions. The wide range of neutron energies increases the challenge because most neutron detectors only sample small energy ranges. Several experiments suggested that neutron-related risk is higher than anticipated.

Summary

The Space Shuttle experiments helped improve the characterization of the radiation environment that enabled scientists to better quantify the risk to astronaut health.

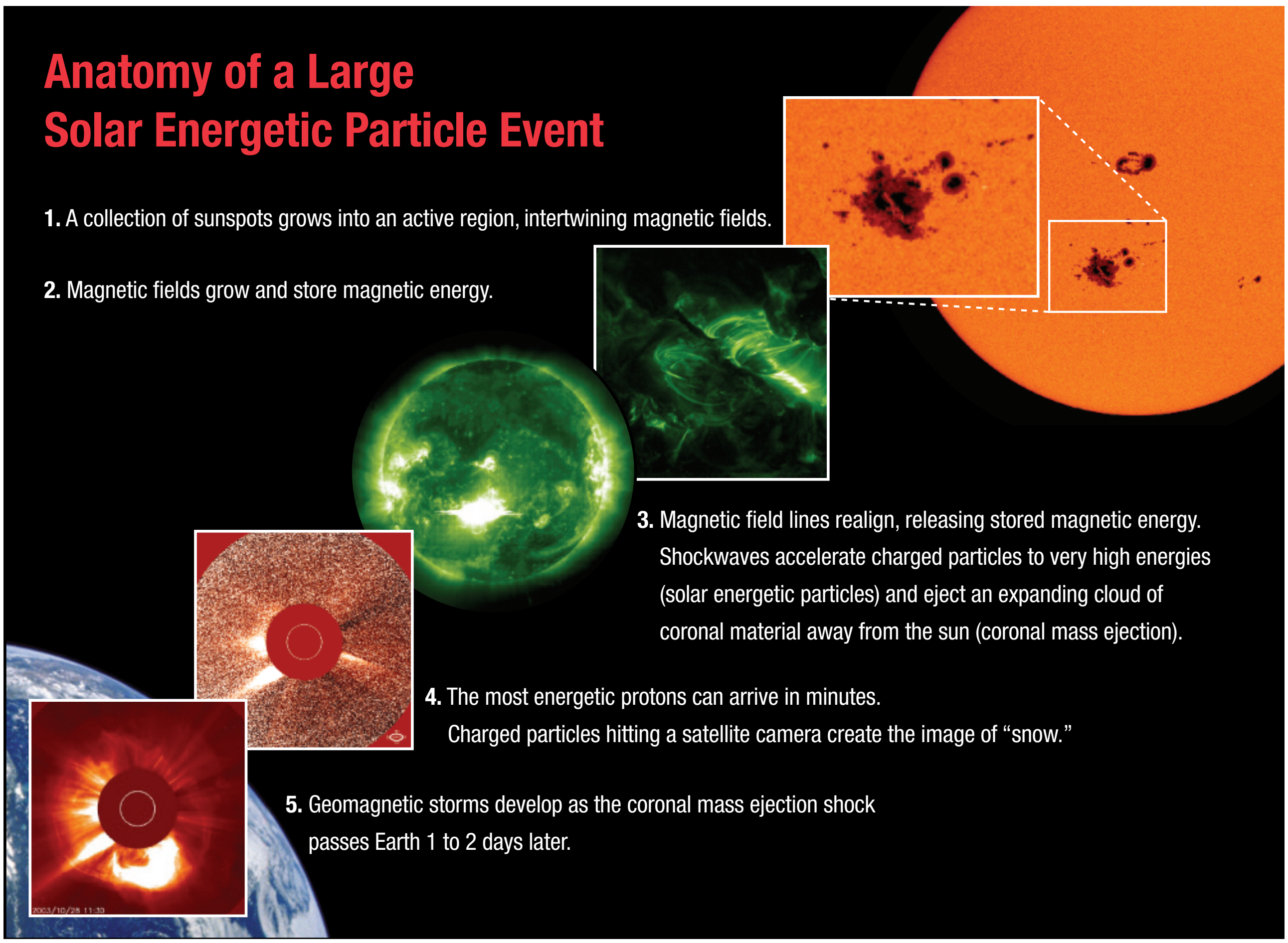
How did Space Weather Affect Astronauts and Shuttle Operations?

So what is space weather? The weather forecaster on the local television channel informs us of the trends and the degree of adverse weather to expect. Space weather is forecasting the trend and degree of changes in the space radiation environment. All dynamic changes in the radiation environment around Earth are driven by processes originating at the sun, such as flares and coronal mass ejections. Magnetic storms, shifts in the intensity and location of trapped radiation, and enhanced levels of solar protons—referred to as solar energetic particle events—are phenomena observed at Earth resulting from solar activity.

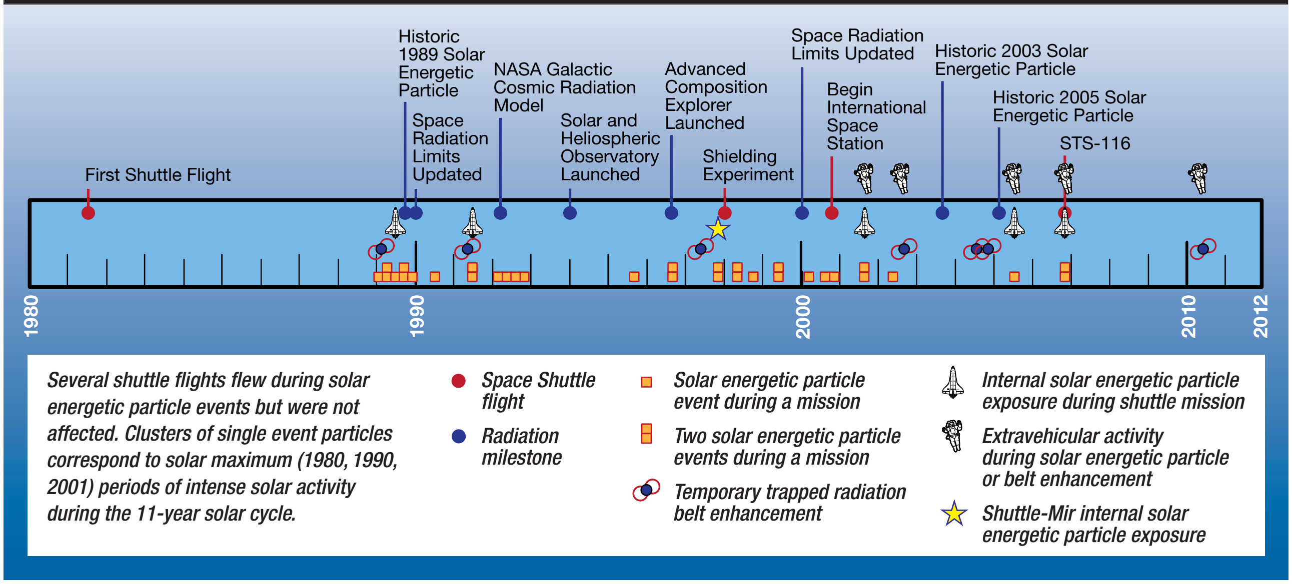
Astronaut health protection from space radiation during shuttle missions required an understanding of the structure, dynamics, and characteristics of the radiation environment. Radiation scientists who supported shuttle missions were as much "space weather forecasters" as they were radiation health physicists.

Space Shuttle Operations and Space Weather

During the course of the Space Shuttle Program, 20 flights (about 15%) were flown during enhanced solar proton conditions. In 1989, a period of maximum solar activity, all five flights encountered enhanced conditions from solar energetic particles; however, astronauts received little additional solar energetic particle dose due to a fortunate combination of orbital inclination, ground track timing, and event size. Almost all solar energetic particle dose exposures to any shuttle



Space Radiation and the Shuttle Flying in Adverse Space Weather



Several shuttle flights flew during solar energetic particle events but were not affected. Clusters of single event particles correspond to solar maximum (1980, 1990, 2001) periods of intense solar activity during the 11-year solar cycle.

astronauts corresponded to less than an extra week of spaceflight daily exposure.

NASA conducted four EVAs supporting ISS construction during the course of solar energetic particle events. Astronauts received very little dose due to orbital timing and the magnitude of the events. The most interesting case occurred during Space Transportation System (STS)-116 in December 2006. NASA conducted this mission at a time when solar activity was at a minimum and solar energetic particle events were considered extremely unlikely. One event occurred just after the crew reentered the space station on the first EVA. A second event initiated while crew members were wrapping up the second EVA. Solar energetic particle exposures for both EVAs were negligible due to ground track timing;

Agencies Work Together to Assess Risks

The Space Weather Prediction Center at the National Oceanographic and Atmospheric Administration and the NASA Space Radiation Analysis Group worked together to support Space Shuttle flights. Space Weather Prediction Center forecasters reviewed available solar and environmental data to assess future environmental trends and provide a daily forecast. The NASA radiation operations group monitored environmental trends as well and reviewed the daily forecast with Space Weather Prediction Center personnel. The Space Radiation Analysis Group then interpreted the forecasted environmental trends and assessed potential impacts to the mission operations much in the way a local weather forecaster applies the National Weather Service forecast to the local area for the public to assess how the weather will impact its planned activities. During dynamic changes in the radiation environment, the radiation operations group tracked the progress of the event and advised the flight team when conditions warranted contingency procedures.

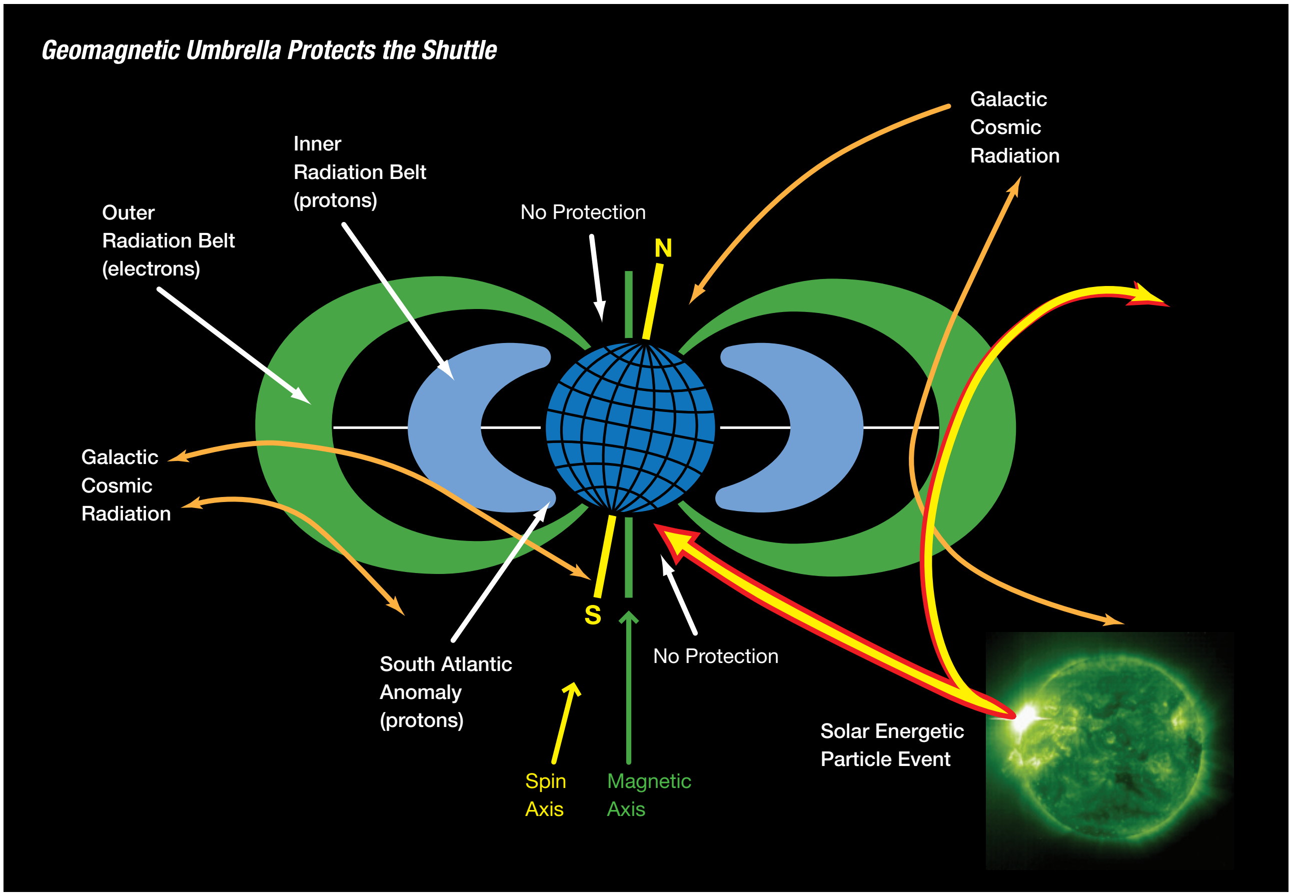
however, if the EVAs had been scheduled 3 hours later, the story would have been much different.

Inclination and ground track timing influence the degree of impact of a solar energetic particle. Flight inclination is the angle between the orbital plane and the equator. Inclination defined what ground track latitudes the orbit flew between. Low-inclination flights traveled between latitudes of 28.5 degrees to approximately 40 degrees. High-inclination flights flew between latitudes greater than 50 degrees. The geomagnetic field provided considerable protection to flight crews that flew low-inclination flights because the charged particles could not penetrate to the shuttle orbit. STS-34 flew in October 1989 during one of the historically largest solar energetic particle events but was unaffected by it because the geomagnetic field protected the low-inclination mission.

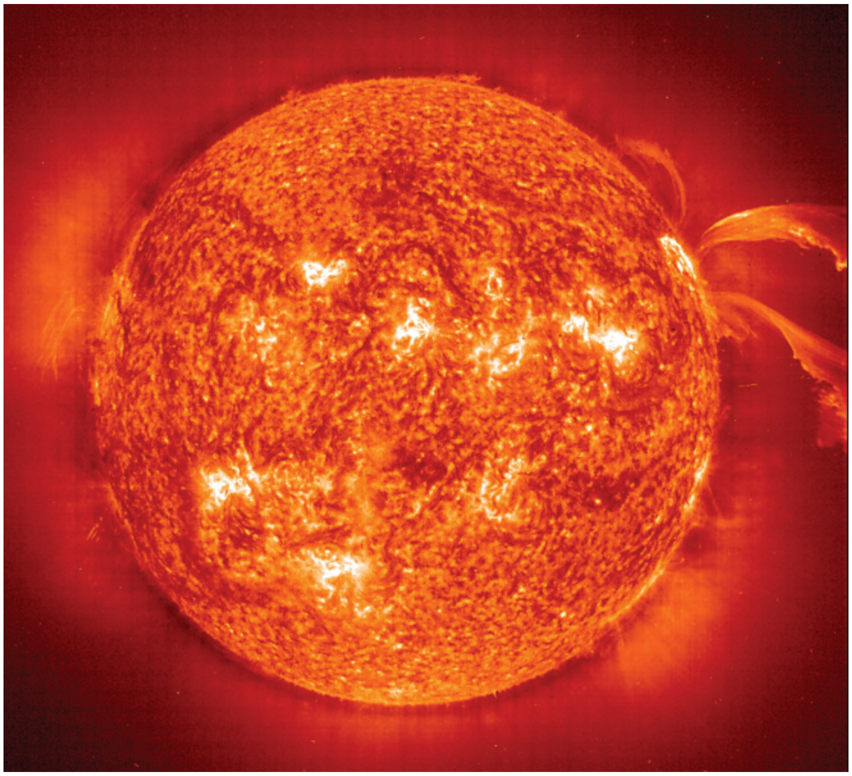
High-inclination missions, such as those to the ISS, flew through regions of virtually no geomagnetic protection. When the shuttle flew through those orbital regions during solar energetic particle events, the crew was exposed to solar energetic particle protons. During the remainder of the orbit, the crew was protected by the geomagnetic field and received no solar energetic particle dose.

Magnetic storms increase the size of the regions of no magnetic protection. A severe magnetic storm could have resulted in increased time spent in low protection, resulting in three times the exposure.

The good news is that high-risk time intervals of low geomagnetic protection can be accurately predicted, thus



From strong protection at the equator to no protection at the poles, Earth's magnetic field provided considerable radiation protection to the shuttle by deflecting solar and galactic cosmic radiation. Usually, the shuttle was well protected; however, when the shuttle flew beyond 45 degrees latitude, there was usually little or no magnetic protection. The magnetic field also defined the regions of trapped radiation.



A pair of curving, erupting solar prominences on June 28, 2000. Prominences are huge clouds of relatively cool dense plasma suspended in the sun's hot, thin corona.

enabling operational response planning. Although the solar energetic particle magnitude cannot be predicted, the time intervals of when the crew will be subject to exposure can be quickly determined. If the particle is large and it is prudent for the crew to move to higher shielded areas of the station, shelter would be recommended.

Fortunately, the average exposure to shuttle crews—around 0.5 rem (5 mSv)—was far lower than the maximum exposure guideline of 25 rem/month (250 mSv/month) and also fell below the quarterly terrestrial exposure limits. During the course of the Space Shuttle Program, crew radiation exposures ranged from 0.008 rem (0.08 mSv) to 6 rem (60 mSv). The 10-day, high-altitude Hubble Space Telescope mission approached an exposure similar to an average 180-day mission to the ISS, which was 8 rem (80 mSv).

In all, operational tools and procedures to respond to space weather events matured during the course of the Space Shuttle Program and are being applied to space station operations.

Summary

During the Space Shuttle Program, great strides forward were gained in the operational effectiveness for managing radiation health protection for the astronauts. Knowledge gained via experiments vastly improved the characterization of the environment and illuminated factors that contribute to defining health risks from exposure to space radiation. These lessons will greatly benefit future generations of space travelers.