

# Major Scientific Discoveries

**The Space Shuttle and Great Observatories**



**Atmospheric Observations and Earth Imaging**



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# The Space Shuttle and Great Observatories

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***Space Shuttle Bestows On Hubble the Gift of “Perpetual Youth”***

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*NASA’s “Great Observatories” are symbolic of our urge to explore what lies at the edge of the universe, as we know it. Humans had stared at the stars for centuries before the advent of simple telescopes brought them a little closer to the amazing formations in our solar system. Telescopes became larger, technologies were developed to include invisible wavelengths from the shortest to longest, and locations of instruments were carefully chosen to gain better sights and insights into our vast universe. Then, the Space Age dawned and we sent humans to the moon. The desire to explore our universe became even more intense. NASA probes and rovers landed on destinations in our solar system—destinations we once thought remote and beyond reach. These initiatives forever changed our perception of the solar system and galaxies.*

*Scientists have long desired space-based observation platforms that would provide a better view of our universe. NASA’s Great Observatories (satellites) are four large and powerful space-based telescopes that have made outstanding contributions to astronomy. The satellites are:*

- *Hubble Space Telescope*
- *Compton Gamma Ray Observatory*
- *Chandra X-ray Observatory*
- *Spitzer Space Telescope*

*Of these, only the Spitzer Space Telescope was not launched by the Space Shuttle. In June 2000, the Compton Gamma Ray Observatory was deorbited and parts splashed into the Pacific Ocean.*

*While Hubble has become the people’s telescope due its public and media impact, all the Great Observatories made enormous science contributions including: new wave bands; high-resolution, high-sensitivity observations; and a sharper, deeper look into distant galaxies.*



## ***Space Shuttle Bestows On Hubble the Gift of “Perpetual Youth”***

The Space Shuttle and Hubble Space Telescope were conceived and advocated as new NASA programs in the same era—roughly the late 1960s and the decade of the 1970s. It was recognized early on that a partnership between the Hubble program and the Space Shuttle Program would be mutually beneficial at a time when both were being advocated to Congress and the Executive Branch.

A telescope designed to be periodically serviced by astronauts could be viewed as a “permanent” astronomical observatory in space, modeled after the observatories on Earth’s surface. At Hubble’s core would be a large, high-quality optical telescope that, with its surrounding spacecraft infrastructure periodically serviced by shuttle crews, could have an operating lifetime measured in decades. Its heart would be scientific instruments that could be regularly replaced to take advantage of major advances in technology. Thus, the shuttle brought to Hubble the prospect of a long life and, at the same time, the promise of “perpetual youth” in terms of its technological prowess.

Hubble provided a splendid example of the value of the shuttle in allowing regular access to low-Earth orbit for a large crew and heavy payloads. The shuttle enabled modes of working in space that were not otherwise possible, and the Hubble program was both the proof of concept and the immediate beneficiary. The two



*Hubble Space Telescope after capture by STS-61 (1993).*

programs represented the nexus of human spaceflight and robotic exploration of the universe.

Hubble’s design was optimized with its relationship to the shuttle in mind. The optical telescope and surrounding structure needed to be small enough to fit into a shuttle payload bay. On the other hand, the scientific value of the telescope hinged on making its aperture as large as possible. The final aperture size, 2.4 m (7.9 ft), was large enough to allow one of the observatory’s most important science

objectives—precisely measuring the distance scale and age of the universe—yet could be packaged to fit inside the shuttle payload bay.

Many of the Hubble spacecraft’s subsystems were designed in modular form, and were removable and replaceable with relative ease by astronauts in spacesuits. However, this was not the case for every subsystem. One of the most telling demonstrations of the value of human beings working in space comes from the creativity and ingenuity of the astronauts and



their engineering colleagues on the ground in devising methods for replacing or repairing components that were not designed to be worked on easily in orbit.

It is well known that Hubble, launched in 1990, was seriously defective. Its 2.4-m (7.9-ft) primary mirror—a beautifully ground and polished optic—was accidentally ground to the wrong prescription. The result, which became apparent when the newly launched telescope first turned its gaze to starlight, was a blurry image that could not be corrected with any adjustments in the telescope’s focus mechanism or with the 24 actuated pressure pads placed under the primary mirror to adjust its shape, as needed. The erroneous curvature of the mirror produced a common form of optical distortion called “spherical aberration.” In addition, Hubble’s two flexible solar arrays shuddered significantly due to thermal stresses introduced every time the spacecraft passed from darkness to daylight or vice versa. This phenomenon introduced jitter into the pointing of the telescope, further smearing out its images.

In the years immediately after Hubble’s deployment, the observatory did produce some interesting astronomical science but nothing at all like what had been expected throughout its design and development. It quickly became a national embarrassment and the butt of jokes on late-night talk shows.

It is interesting to consider how the history of Hubble and NASA might have transpired if the spacecraft had not been designed as an integral part of the world of human spaceflight but, rather, had been launched with an expendable rocket and not been

serviceable in space. The scandal and embarrassment would likely have persisted for a while longer and then faded as the less-than-memorable science being produced also faded from public interest. One wonders if the champions of the Hubble mission could have stimulated the political and public will to try again—to develop and launch a second Hubble. Certainly, any such project would have taken a decade or longer and required new expenditures of public funds, probably \$2 billion or more. In any event, the original Hubble Space Telescope would have long ago failed and today would be orbiting Earth as a large and expensive piece of space junk.

Hubble’s history has played out in an entirely different and much more satisfying manner precisely because it was built to be cared for by human beings in low-Earth orbit. Scientists and engineers quickly identified the nature of Hubble’s optical flaw and created optical countermeasures to correct the telescope’s eyesight. The European Space Agency devised a new thermal design to mitigate the jitter-inducing flexure of the European solar arrays. The time required to design, fabricate, test, and fly these fixes to Hubble on the first servicing mission was approximately 3.5 years. In late 1993, public scorn turned into adulation, both because of the exquisite imagery that a properly performing Hubble returned to the ground and the heroism of the astronauts and the dedication of a team of NASA employees and contractors who refused to give up on the original dream of what Hubble could accomplish. The public image of NASA as a “can-do” agency certainly received a major boost. The techniques of working with precision on large structures in space

surely contributed to the acceptance of the feasibility of constructing the International Space Station.

The possibility of periodically servicing Hubble added a degree of flexibility, timeliness, and creativity that was not possible in the world of robotic science missions, which must be planned and executed over periods of many years or even decades. Hubble’s scientific capabilities have never grown out of date because it was regularly updated by shuttle servicing. It is the most in-demand, scientifically successful, and important astronomical observatory in human history, after Galileo’s original telescope. Arguably, it is one of the most important scientific instruments of any kind. There is simply no way this level of achievement could have been possible without the Space Shuttle.



## Hubble—A Work of Ingenuity

On September 9, 2009, NASA declared Hubble to be in full working order following the tremendously successful fifth shuttle mission to service the telescope. As a result of coordination across the extensive Hubble team, the crew of Space Shuttle Atlantis (Space Transportation System [STS]-125) left behind an essentially new telescope with six working instruments. Two superb instruments—the Wide Field Camera 3 and the Cosmic Origins Spectrograph—replaced older devices. Two instruments that had suffered electronic failure in flight were restored to working order through repair activities that, to date, were the most ambitious ever attempted in space. Specifically, the Advanced Camera for Surveys and the Space Telescope Imaging Spectrograph were returned to service to make Hubble the most powerful optical telescope in the world. The STS-125 spacewalks were long and arduous, presenting unforeseen challenges over and above the demanding activities scheduled on the manifest; however, the payoff, seen in the first data, was the reward.

At the launch of STS-125, hopeful astronomers were already planning more research programs using the advanced capabilities of the new telescope. They were confident in the knowledge that over Hubble's 19-year track record, the telescope had greatly surpassed expectations and would continue to do so. Hubble is not the facility that eminent scientist Lyman Spitzer envisioned in the 1940s; it has dramatically exceeded the imagination of all who contributed to the dream of such a capable observatory.

### John Mather, PhD

*Nobel Prize in Physics (2006).  
Senior project scientist for the  
James Webb Space Telescope,  
Goddard Space Flight Center.*

*"The Space Shuttle is a 'brilliant engineering' accomplishment but it was a poor decision on the part of senior leadership as it 'swallowed' other expendable launch vehicles. This decision was not well received by members of the science community.*

*"The Hubble Space Telescope was conceived and designed to be repaired by the shuttle. In that shuttle had brilliant success. What would have been a 'black eye' forever for American science, the shuttle made the capabilities of Hubble 10 times better, over and over with each servicing mission. In addition to the significant repairs, the shuttle greatly expanded the capabilities of the Hubble by upgrading several key components. The upgrades have allowed superlative science to be accomplished from the Hubble. What has been learned from the Hubble is being used in assembling the James Webb Space Telescope. In my view, there would be no Hubble telescope without the Space Shuttle and no James Webb Space Telescope without the Hubble.*

*"In many ways, the most important scientific contribution of the Space Shuttle was that it kept the agency (NASA) alive after the Apollo Program. Thus it kept science alive at NASA indirectly.*

*"Human spaceflight captures people's imagination at gut level. The Space Shuttle was also a product of the Cold War environment of the nation. Humans go into space for more than just science."*



The fidelity of Hubble's wide-field imagery is superb because the telescope's exquisite optical quality is not limited by the jitter and distortion caused by the shifting atmosphere that affect images obtained from the ground. Additionally, as instruments with new technologies—primarily more sensitive light detectors—were placed on board, additional wavelengths of light blocked

by the Earth's atmosphere could be detected in the ultraviolet region of the spectrum where the Earth's atmosphere is opaque, and for some regions of the infrared that suffer from absorption due to water vapor and other molecules.

Hubble has been a crown jewel in the Space Shuttle Program, providing scientific return and unparalleled public



acknowledgment over its lifetime. Launched by STS-31 in 1990, Hubble has contributed to every aspect of astrophysics, achieved its original design goals, and opened new areas of investigation not envisioned in the original proposals for its construction.

Shuttle-enabled refurbishments of Hubble have allowed astronomers to:

- Determine the expansion rate of the universe to 5% accuracy (10% was the goal)
- Discover the existence of dark energy (unexpected) and thus resolve the age of the universe to be 13.7 billion years old
- Identify the host objects for powerful gamma-ray bursts
- Observe some of the deepest images of the cosmos
- Discover protoplanetary disks
- Observe chemical constituents of the atmospheres of planets orbiting other stars
- Characterize the nature of black holes, from supermassive objects in galaxies to stellar-sized objects in star clusters
- Explore numerous views of solar system objects revealing planetary weather and distant dwarf planets still bound to the sun

## Astronomical Terms

**Astronomical unit:** A unit of length used for measuring astronomical distances within the solar system equal to the mean distance from Earth to the sun, approximately 150 million km (93 million miles).

**Black hole:** Formed when the core of a very massive star collapses from its own gravity. A black hole has such a strong pull of gravity that not even light can escape from it.

**Dark energy:** Dark energy is inferred from observations of gravitational interactions between astronomical objects and is not directly observed. It permeates space and exerts a negative pressure.

**Dark matter:** Physicists infer the existence of dark matter from gravitational effects on visible matter, such as stars and galaxies. It is a form of matter particle that does not reflect or emit electromagnetic radiation.

**Galaxy:** A collection of stars, gas, and dust bound together by gravity. The largest galaxies have thousands of billions of stars.

**Light-year:** The distance that light travels in a vacuum in 1 year, approximately 9.46 trillion km (5.88 trillion miles).

**Nebula:** A diffuse mass of interstellar dust or gas or both, visible as luminous patches or areas of darkness depending on the way the mass absorbs or reflects incident radiation.

*Planetary nebulae:* A nebula, such as the Ring Nebula, consisting of a hot, blue-white central star surrounded by an envelope of expanding gas.

**Quasars:** Celestial objects that emit extremely high levels of electromagnetic radiation (including light). The amount of energy emitted by a quasar is higher than even the brightest stars. The closest known quasar is 780 million light-years away.

**Supermassive black hole:** A gigantic black hole, with a mass ranging from millions up to billions of times the mass of our sun, residing at the core of almost every galaxy.

**Supernova:** The explosive death of a massive star whose energy output causes its expanding gases to glow brightly for weeks or months. A supernova remnant is the glowing, expanding gaseous remains of a supernova explosion.

There were early times in the Hubble program, however, when such amazing accomplishments seemed unachievable.

## The Launch of Hubble— First Results

On April 24, 1990, Hubble was launched into orbit with Space Shuttle Discovery (STS-31). The shuttle carried five instruments: the Wide Field Planetary Camera; the Goddard High Resolution Spectrograph; the Faint Object Camera; the Faint Object Spectrograph; and the High Speed Photometer.

During the years of advocacy for the telescope and the subsequent detailed design period, astronomers described some of the amazing results that would be forthcoming from Hubble; however, the much-anticipated first images showed, quite clearly, that something was amiss with the telescope.

Despite their disenchantment, astronomers worked hard to understand and model the Hubble images, and interesting research was accomplished nonetheless. In the first year, the campaign to characterize the nature of black holes in the universe was initiated with the confirmation that a



Shuttle Missions for Hubble Launch, Repair, and Refurbishment					
<b>Launch</b>	<b>Servicing Mission 1</b>	<b>Servicing Mission 2</b>	<b>Servicing Mission 3A</b>	<b>Servicing Mission 3B</b>	<b>Servicing Mission 4</b>
STS-31 Discovery	STS-61 Endeavour	STS-82 Discovery	STS-103 Discovery	STS-109 Columbia	STS-125 Atlantis
					
	Wide Field Planetary Camera 2 Corrective Optics Space Telescope Axial Replacement Gyros Solar Arrays	Space Telescope Imaging Spectrograph Near Infrared Camera and Multi-Object Spectrometer Fine Guidance Sensor Solid State Recorder	Advanced Computer Gyros Fine Guidance Sensor	Advanced Camera for Surveys Near Infrared Camera and Multi-Object Spectrometer Cooling System Power Control Unit Solar Arrays	Wide Field Camera 3 Cosmic Origins Spectrograph Space Telescope Imaging Spectrograph Repair Advanced Camera for Surveys Repair Science Instrument Command and Data Handling Unit Gyros New Outer Blanket Layer Soft Capture Mechanism Batteries Fine Guidance Sensor
					
April <b>1990</b>	December <b>1993</b>	February <b>1997</b>	December <b>1999</b>	March <b>2002</b>	May <b>2009</b>

supermassive black hole with mass about 2.6 billion times the mass of the sun resides in the center of the giant elliptical galaxy M87. This result was based on Wide Field Planetary Camera and Faint Object Camera imagery and Faint Object Spectrograph spectroscopy. In addition to that scientific result, optical counterparts of radio jets in galaxies were resolved, spectroscopic observations helped to disentangle the nature of intergalactic clouds absorbing light from near and far galactic systems, and the monitoring of surface features of solar system planets was initiated.

### Servicing Mission 1

To correct for the telescope's optical flaw, Hubble scientists and engineers designed and fabricated a new instrument, the Wide Field Planetary Camera 2, and another device called Corrective Optics for Space Telescope Axial Replacement, the latter intended to correct the instruments already on board. The first Hubble servicing mission (STS-61 [1993]) was the ambitious shuttle flight to install the corrective optics and resolve other spacecraft problems. It was a critical mission for NASA. The future of

the Hubble program depended on the astronauts' success, and the Space Shuttle Program hung in the balance as well as the future of the agency. The struggle to keep the first repair mission funded was a day-by-day battle that served to cement the cooperation between NASA and the university research community.

As the first images came into focus, overjoyed researchers and engineers began to gain confidence that the promise of Hubble could now be realized.



### ***New Results After Servicing Mission 1***

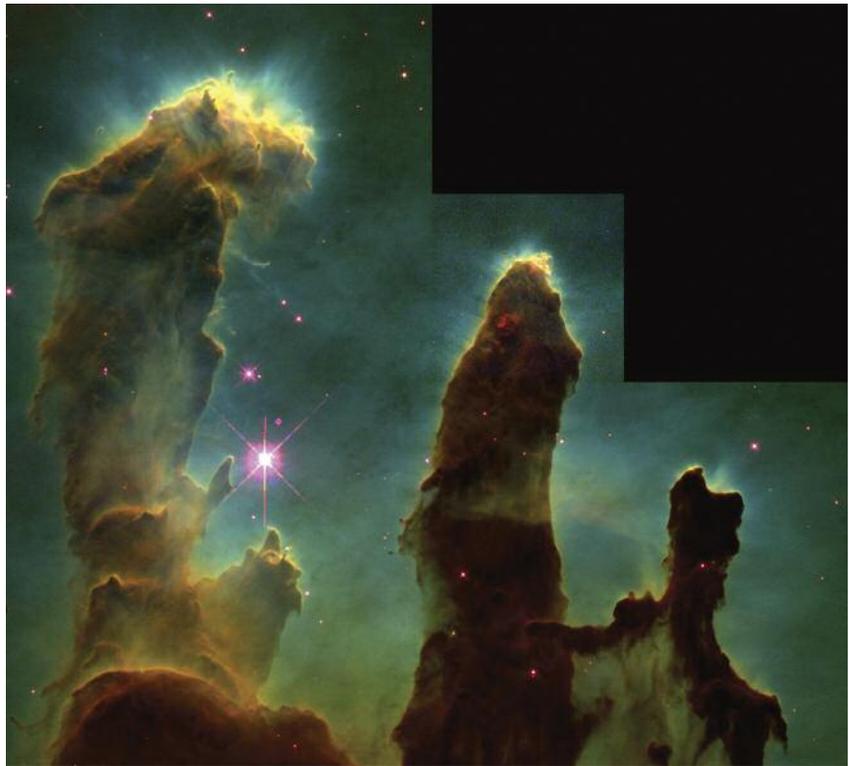
Immediately, NASA obtained impressive results. For example, Wide Field Planetary Camera 2 images of the Orion Nebula region resolved tiny areas of compact dust around newly formed stars. These protoplanetary disks, sometimes called *proplyds*, were the first hint that Hubble would contribute in a significant way to the studies of the formation of extrasolar planetary systems. In another observation, Hubble detected a faint galaxy around a luminous quasar (short for quasi-stellar object), suggesting that luminous quasars and galaxies were fundamentally linked. In our own galaxy, the core of an extremely dense, ancient cluster of stars—the globular cluster 47 Tucanae—was resolved, demonstrating definitively to the skeptical scientific community that individual stars in crowded fields could be distinguished with the superb imaging power of Hubble.

### ***Shoemaker-Levy***

Early Hubble observations of solar system objects included the spectacular crash of Comet Shoemaker-Levy 9 into Jupiter in 1994. This event was witnessed from start to finish, from the first fragment impact to the aftermath on the Jovian atmosphere. Images were



*Color image of Jupiter showing the effect of the several impacts of Comet Shoemaker-Levy 9 after its multiple fragments impacted the planet in 1994.*



*Gas pillars in the Eagle Nebula: Pillars of Creation in star-forming region captured by the Wide Field Planetary Camera 2 in 1995. The region is trillions and trillions of miles away in the constellation Serpens. The tallest pillar is 4 light-years long and the colors show emissions from different atoms.*

also taken in visible blue light and ultraviolet light to determine the depth of the impacts and the nature of Jupiter’s atmospheric composition.

### ***Pillars of Creation***

The famous “Pillars of Creation” image of the Eagle Nebula captured the public imagination and contributed to the understanding of star-formation processes. The images captured in 1995 with Wide Field Planetary Camera 2 showed narrow features protruding from columns of cold gas and dust. Inside the gaseous “towers,” interstellar material collapsed to form young stars. These new hot stars then heated and ionized the gas and blew it away from the formation sites. The dramatic scene, published in newspapers far and wide, began to redeem the public reputation of Hubble.

### ***Existence of Supermassive Black Holes***

From ground-based data, scientists knew that galaxies exhibit jets and powerful radio emission that extends well beyond their optical periphery. Huge x-ray emissions and spectroscopic observations of galaxies suggested that some of these objects might contain a large amount of mass near their centers. Even Wide Field Planetary Camera 2 observations of the innards of several galaxies suggested that black holes might be hidden there. However, it was the observation of the giant elliptical galaxy M87 with the Faint Object Spectrograph that conclusively demonstrated that supermassive black holes exist in large galaxies. This was the turning point in



black hole studies, with spectroscopy being the powerful diagnostic tool astronomers could use to begin the Hubble census of these exotic objects.

### **Building Blocks of Early Galaxies**

One of the planned goals for Hubble research was to understand the nature of the universe and look back in time to the earliest forming galaxies. In December 1995, 2 years after the first servicing mission, Hubble's Wide Field Planetary Camera 2 was pointed at a field in Ursa Major for 10 days, accumulating 342 exposures. The final image—the Hubble Deep Field—was, at the time, the deepest astronomical image ever acquired. The field probes deep into the universe and contains over 1,500 galaxies at various distances.

After the Hubble Deep Field data were produced, telescopes were pointed at the same part of the sky to obtain data in every conceivable way. Besides bolstering the idea that galaxies form from building blocks of smaller components that are irregularly shaped and that the rate of star and galaxy formation was much higher in the past, analysis of the data pushed the observable universe back to approximately 12 billion years. Papers written on Hubble Deep Field data alone number in the hundreds and document a new understanding of cosmological and astrophysical phenomena.

The immediate release of Hubble Deep Field data represented a watershed in astronomical research as well. A new method was born for concentrating astronomical facilities and the collective brainpower of the scientific community on a specific research problem. Thus, the Hubble Deep Field represents not only a leap forward in scientific understanding of the universe, but a significant alteration in the way astronomy was conducted.



### **Edward Weiler, PhD**

*Chief scientist for the Hubble Space Telescope (1979-1998).*

*NASA associate administrator, Science Mission Directorate.*

*"It's fair to say that Hubble, today, would be a piece of orbiting space debris if it hadn't been for the Space Shuttle Program. If Hubble had been launched on an expendable launch vehicle, we would have discovered the optical problem yet been unable to fix it.*

*Hubble would have been known as one of the great American scientific disasters of our time. Hubble's redemption is due to the Space Shuttle Program and, most importantly, to the astronauts who flew the shuttle and did things (in repairing Hubble) that we never thought could be done in space. Hubble became a symbol of excellence in technology and science, and the shuttle made that happen.*

*"I've spent 34 years on Hubble in one way or another. I was on top of Mount Everest at the launch, with all of us astronomers who had never done an interview. I was on the Today Show and Nightline on the same day. I experienced the ecstasy in April 1990, to the bottom of the Dead Sea 2 months later when a spherical aberration was detected in the Hubble. In our hearts, we knew we could fix it. We promised the press we would fix it by December 1993, and nobody believed us. Then, on December 20, 1993, we saw the first image come back. It was spectacular. It was fixed. And the rest is history. We went from the bottom of the Dead Sea back to the top of Mount Everest and beyond...we were elated!"*

## **Subsequent Servicing Missions**

### **Servicing Mission 2**

By the end of 1996, Hubble was a productive scientific tool with instruments for optical and ultraviolet astronomy. During the second servicing mission in February 1997, the STS-82 crew installed two new scientific instruments: the Near Infrared Camera and Multi-Object

Spectrometer, extending Hubble's capabilities to the infrared, and the Space Telescope Imaging Spectrograph, offering ultraviolet spectroscopic capability. Astronomers now expanded their research to probe astrophysical phenomena using the excellent imaging performance of Hubble coupled with new capability over a larger range of wavelengths.



### ***Servicing Missions 3A and 3B***

The third servicing mission was intended to replace aging critical telescope and control parts to retain Hubble's superb pointing ability and to install new computer equipment and a new instrument; however, when a third (out of six) gyroscope on Hubble failed—three gyros are needed for target acquisition—NASA elected to split these missions into two parts. To add to the drama, a fourth gyroscope failed on November 13, 1999. Hubble was safe, but it could not produce scientific observations. Another bit of tension was created by concern about the transition to the year 2000 and the hidden computer problems that might occur. Just in time, on December 19, 1999, Space Shuttle Discovery (STS-103) delivered new gyroscopes, one fine guidance sensor, a central computer, and other equipment, restoring Hubble to reliable operation and making it better than ever.

The next servicing mission occurred during March 2002 when Space Shuttle Columbia (STS-109) was launched to further upgrade the telescope. The new science instrument, the Advanced Camera for Surveys, was installed with a wide field of view, sharp image quality, and enhanced sensitivity. The Advanced Camera for Surveys field was twice that of the Wide Field Planetary Camera 2 and collected data 10 times faster. The astronauts also installed new solar array panels, a power control unit, and a new cooler for the Near Infrared Camera and Multi-Object Spectrometer to extend its life. They also installed a refurbished Fine Guidance Sensor and a reaction wheel to ensure telescope steering and fine pointing.

### ***Hubble Deep Field and Hubble Ultra Deep Field***

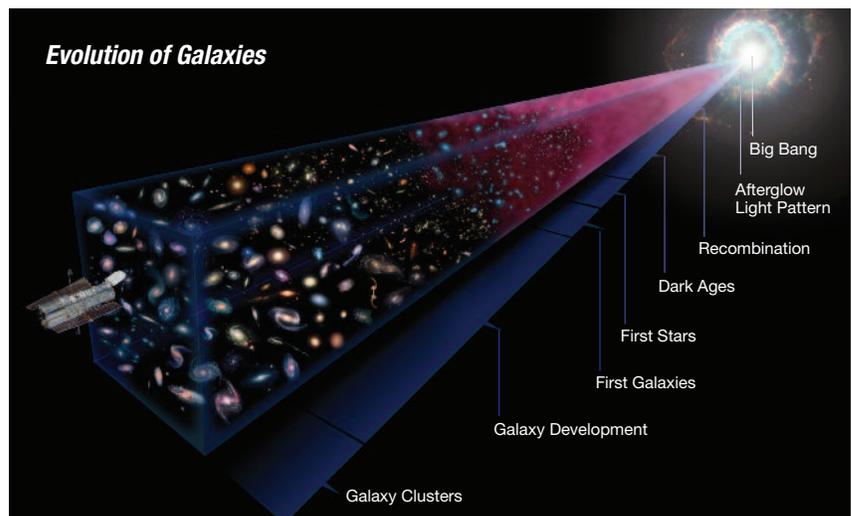
With the new infrared capability installed during the second servicing mission, astronomers turned the Near Infrared Camera and Multi-Object Spectrometer to view part of the original Hubble Deep Field for a series of long exposures. Extremely distant objects were revealed, objects that had been undetected in the optical Hubble Deep Field because their light was red-shifted due to the expansion of the universe. The original Hubble Deep Field is located in the northern celestial hemisphere. In 1998, NASA added a second field, the Hubble Deep Field-South, to the collection. The second field represented another “core



*The Hubble Ultra Deep Field showing thousands of galaxies reaching back to the epoch when the first galaxies formed.*

sample” of the universe compared and contrasted to the northern observation to verify that Hubble Deep Field-North is representative of the universe in general. Researchers took advantage of Space Telescope Imaging Spectrograph and Near Infrared Camera and Multi-Object Spectrometer cameras to obtain deep adjacent fields as additional samples of the universe in the ultraviolet and infrared.

After astronauts installed Advanced Camera for Surveys during the third servicing mission, astronomers pushed the limits of observation even further in an additional field called the Hubble Ultra Deep Field. Deep Advanced Camera for Surveys and Near Infrared Camera and Multi-Object Spectrometer data revealed thousands of galaxies, some of which existed a mere 800 million years after the Big Bang. The optical detections reached 31 to 32 magnitudes, at least seven times deeper than ever before, and there were hints from the new Near Infrared Camera and Multi-Object Spectrometer data that galaxies as young as a few million years after the creation of the universe were detected. Observations with NASA's Spitzer Space Telescope produced deep images of the Hubble Ultra Deep Field in the infrared. These data were analyzed



*Schematic of Hubble sampling galaxies through space and time.*

along with the Hubble data to provide a more complete catalog of very distant galaxies with the result that at least one surprisingly massive galaxy was identified in the field where only small “precursor” galaxies were expected.

Astronomers were quick to test that result using Wide Field Camera 3, deployed during a servicing mission. The faintest galaxies found are blue and should be deficient in heavy elements, meaning they are from a population that formed extremely early when the universe was only 600 million years old. More data from Wide Field Camera 3 may reach even 100 million years earlier. Beyond that, astronomers anticipate continuing to push earlier in the universe with the launching of the James Webb Telescope.

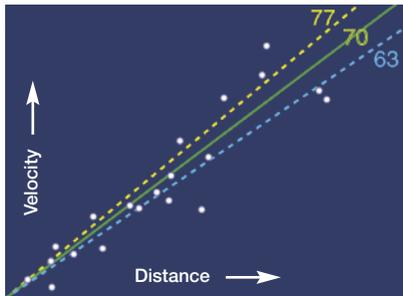
### Age of the Universe

The cornerstone investigation to be carried out by Hubble was the determination of the age of the universe. Previous work provided a wide range for this age: from 10 to 20 billion years old—a factor of two. Hubble research was to address one of the most basic questions about the cosmos, and further refinement was to be based on more accurate measurement of the cosmological expansion rate; i.e., the Hubble constant. From this expansion rate, the age of the universe can be determined by tracing the expansion back to the origin of cosmos. In fact, this key project was used as prime justification for fabrication of the telescope.

In particular, it was well known that data for variable stars called Cepheids were critical to answer this fundamental question. Cepheid variables were discovered in the early 1900s when Henrietta Leavitt studied photographic plate material while working at the Harvard College Observatory. She



*The spiral galaxy NGC 4603 is the most distant galaxy used to study the pulsating Cepheid variables for the Hubble constant study. This galaxy is associated with the Centaurus cluster, one of the most massive groupings of galaxies in the closer universe. This image was assembled from Hubble Wide Field Planetary Camera 2 data obtained in 1996 and 1997.*



*This Hubble Diagram for Cepheids shows a plot of galaxy distance (determined from the Cepheid variables in it) vs. the velocity that the galaxy appears to be receding from Earth (determined from spectroscopy). The graph shows that the value of Hubble constant is the best fit from the key project observations.*

carefully compiled a list of stars that changed brightness regularly in the nearby Large and Small Magellanic Clouds, companion galaxies to our own Milky Way. While classifying the subset of variable stars that were Cepheids, she noticed that objects with longer periods of variation were brighter. Her “period-luminosity” relation is the basis for the use of Cepheids as a standard to be used for distance measurements. Before Hubble observations were taken, distances to nearby galaxies had been determined from Cepheids using ground-based telescopes to map the local structure, motions, and expansion.

Since the results from many previous studies of the nearby universe produced such disparity, a goal of the Hubble observational program was to push the measurements out farther to more distant, fainter objects and determine Hubble constant with greater accuracy. It also was understood at the time of the launch of Hubble that the oldest objects known, the globular clusters, had ages of about 15 billion years, and this result served as an independent measure of the age of the universe (the universe has to be at least as old the objects in it).

The key project team measured superb resolution Hubble Wide Field Planetary Camera 2 images over many years. The team identified nearly 800 Cepheids in 18 galaxies out to 65 million light-years. Data from 13 other galaxies were combined for a total of 31 galaxies with measured distances. The recession velocity of each galaxy was plotted against each galaxy’s distance as measured from the Cepheids for a self-consistent measurement. This plot indicated the expansion rate exhibited by the benchmark galaxies was within 10% of Hubble constant. The results, published in 2001, also compared favorably with the Hubble flow calibrated with several secondary distance indicators that could also be used in more remote objects. Type Ia supernova is a category of cataclysmic stars that formed as the violent explosion of a white dwarf star. It produces consistent peak luminosity and is used as standard candles to measure the distance to their host galaxies. The brightnesses of Type Ia supernovae, being much brighter than Cepheids, are critical for measuring Hubble constant at even larger distances, and those measurements could be combined with the Cepheid values. At that point, one of Hubble’s major objectives was achieved.

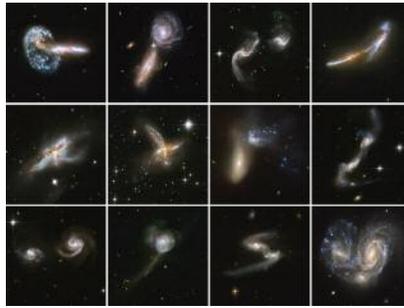


While the measurements of Hubble constant were converging to a consistent value, the simplest cosmological model in favor (the Einstein-de-Sitter model), used to convert the expansion rate into an age for the universe, resulted in a value of about 9 billion years. The situation was clearly impossible. The ever-refined globular cluster ages dropped slightly with better understanding of stellar astrophysics, but the big question in cosmology remained: 13 billion or 9 billion? The quandary was finally resolved for the most part with the discovery that the expansion rate is changing over time and the universe is actually accelerating, so the age derived from the simple model is not correct. The new model, which accommodates this circumstance, has resolved the discrepancy, resulting in an age of the universe of 13.7 billion years that is consistent with the independent globular cluster ages.

The story is not complete, however. A study reported in 2009, using Near Infrared Camera and Multi-Object Spectrometer data, produced a value of Hubble constant to within 5% uncertainty. This measurement represents a factor of two in improvement and is in general agreement with the key project report. The acceleration and age of the universe will continue to be investigated and refined. Thus, the determination of Hubble constant and the detailed nature of the expansion of the universe will be important research topics for future Hubble studies.

### **Interacting Galaxies**

Galaxies occur in a variety of environments: small groups, such as those surrounding our own Milky Way; medium-sized and large clusters; and tight formations of interacting objects.



*A small selection of the hundreds of interacting galaxies observed by Hubble.*

The study of interacting or colliding galaxies yields information about how galaxies may have formed and merged in the early universe and how star formation is triggered across the span of a spiral galaxy's disk. From the first days of Hubble observations to years later, magnificent images of pairs, groups, and small clusters of galaxies have been obtained for this research.

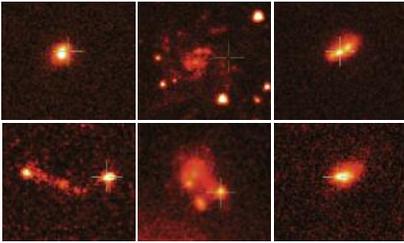
### **Gamma-ray Bursts**

Knowledge of the existence of energetic bursts of emission in gamma rays from all across the sky was traced to the 1960s with the serendipitous detection of gamma-ray bursts by the US Vela satellites designed to detect gamma rays from nuclear weapon tests. The nature of the bursts was enigmatic and posed a problem for astrophysics once it was understood that the energy originated from somewhere in the sky. Data from the Burst and Transient Source Experiment instrument of the Compton Gamma Ray Observatory, launched in 1991, represented a watershed in understanding by demonstrating that gamma-ray bursts come from *everywhere* in the sky. The search was on until 1997 when another gamma-ray satellite, BeppoSAX, with an Italian/Dutch instrument, detected a gamma-ray burst called GRB 970228 associated with a fading x-ray emitter. The breakthrough in understanding

came as scientists identified the optical counterpart in Hubble images and realized that the source resided in a distant galaxy. Hubble monitored the object and traced its rate of fading over time. The observations demonstrated that although the source was in a distant galaxy, it was not near its center, suggesting that the bursts were associated with a single object but not the galaxy's nucleus.

Hubble research identified a number of gamma-ray bursts over time, and all were attributed to objects in distant galaxies. For example, a staggeringly bright object in a host galaxy was identified with Wide Field Planetary Camera 2 after detections by the BeppoSAX and Compton satellites in 1997. In general, Hubble data are used to monitor the fading of the object months after the initial burst, when the emission is no longer observable by other facilities. An accumulation of such observations of over 40 objects with Space Telescope Imaging Spectrograph, Wide Field Planetary Camera 2, and, later, Advanced Camera for Surveys clarified that "long-duration" gamma-ray bursts reside in the brightest regions of small, irregular galaxies. The analysis suggests that the progenitors are massive stars, roughly 20 or more times the mass of the sun, in regions with a dearth of heavy chemical elements. Overall, gamma-ray bursts appear associated with some sort of stellar collapse sometimes involving magnetic fields and the creation of stellar black holes, often associated with supernovae explosions.

Hubble Wide Field Planetary Camera 2 recorded the brightest supernova gamma-ray burst that could be seen with the naked eye halfway across the universe. The explosion was so far away, it took its light 7.5 billion years to reach Earth. In fact, the explosion



*Hubble images probing the environments of gamma-ray burst detections found that long-duration events are located in small, faint, misshapen, (irregular) galaxies, which are usually deficient in heavier chemical elements. Only one of the bursts was spotted in a spiral galaxy like our Milky Way. The burst sources are concentrated in the brightest regions of the host galaxies, suggesting they may come from some of the most massive stars, for example those that are 20 times the mass of the sun.*

took place so long ago that Earth had not yet come into existence. This object may be a star more than 50 times the mass of the sun that had exploded much more violently than the “usual” supernovae. These objects, called *hypernovae*, fade more slowly than other gamma-ray bursts.

### **Black Hole Census**

Astronomers had avidly searched for the existence of black holes in galaxies with a variety of instrumentation and telescopes, and it was spectroscopic observations of large galaxies that revealed that supermassive black holes might be quite common. After servicing mission 2, astronomers were able to employ a full suite of Hubble instruments to continue the ongoing inventory of black holes in galaxies. Researchers eventually inferred that the smaller black holes exist in smaller galaxies, so that a correlation between galaxy size and black hole mass was uncovered. Near Infrared Camera and Multi-Object Spectrometer and Wide Field Planetary Camera 2 data uncovered evidence for black holes in a growing list of objects. The detailed

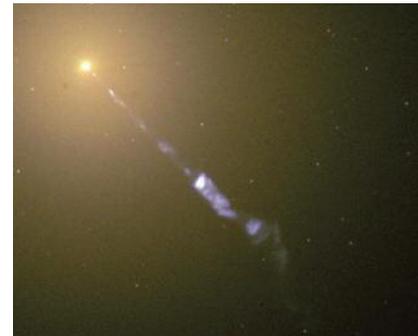
profiles of black holes were traced with spectroscopic data from Space Telescope Imaging Spectrograph. Astronomers observed material surrounding the cores of numerous galaxies. This material exhibited features particular to material spiraling into black holes. In addition, jets, bubbles, and dense star clusters were detected. A black hole also was discovered in our own galaxy’s nearby companion, M31. The exotic nature of star clusters close to the black hole in the center of the Milky Way was characterized through infrared observations with Hubble. The picture that emerged is that black holes are pervasive in the center of galaxies rather than a rarity. Giant elliptical galaxies and spiral galaxies with enormous bulge components seem to be the hosts of supermassive black holes, whereas galaxies such as the Milky Way, with smaller bulges, have smaller black holes. Another link between galaxies and black holes is that it now appears that very active nuclei, called active galactic nuclei, and luminous quasars are linked to black hole and galaxy formation.

The black hole in the center of the giant elliptical galaxy M87 is the best studied with Hubble. Since Hubble was first launched, the instruments on board have been used to image the detail of the galaxy’s core, the structure of its jet, and, more recently, the flare-up of the jet as observed with Advanced Cameras for Surveys and Space Telescope Imaging Spectrograph. The mysterious brightening and fading is likely due to activity around the black hole.

Astronomers also have pushed Hubble to observe smaller-sized black holes; for example, mapping the chaotic fluctuations in the ultraviolet light exhibited by Cygnus XR-1, one of the first stellar black holes known. The observations verified the existence of material sliding through the event



*Image of the entire galaxy M87 taken with Advanced Camera for Surveys.*



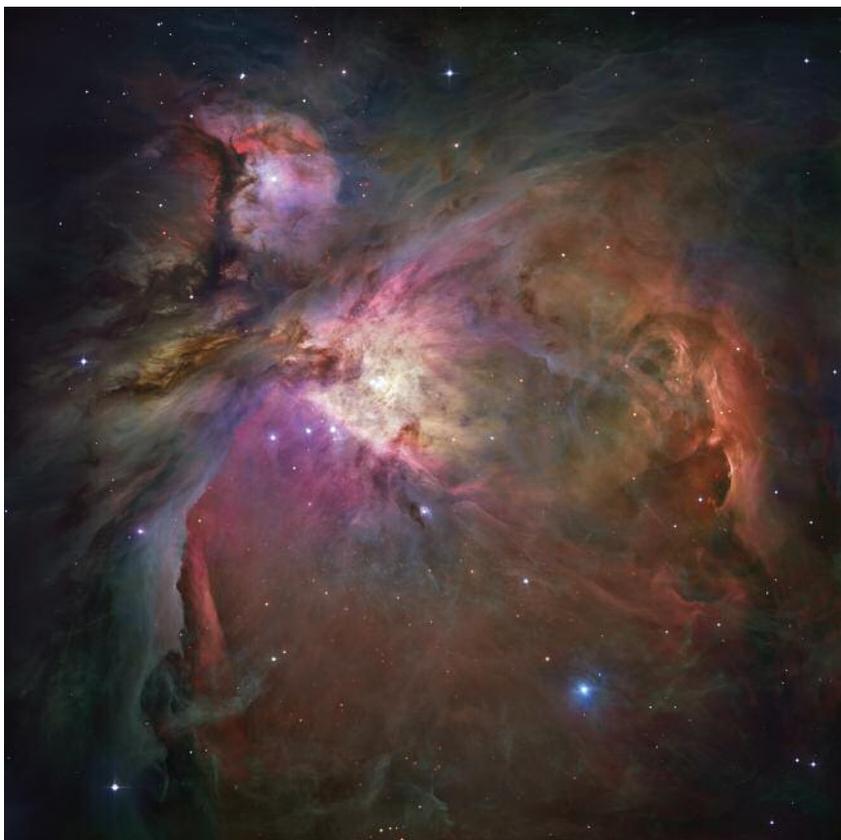
*Detail of the jet and tight core containing an enormous black hole in the giant elliptical galaxy M87 reobserved with Hubble’s Wide Field Planetary Camera 2.*

horizon of the black hole. Apparently, medium-sized stellar black holes do exist as well, as determined from Wide Field Planetary Camera 2 images and Space Telescope Imaging Spectrograph spectroscopic observations of the globular cluster M15. Since these star clusters contain the oldest stars in the universe, they probably contained black holes when they originally formed. An intermediate-mass black hole was similarly discovered in the giant cluster “G1” in M31. With improvements in instrumentation coupled with excellent pointing stability, the multiyear Hubble black hole campaign has provided insights into the black holes in the violent cores of galaxies and possible linkages to stellar-mass black holes formed in the early universe.



## Star Formation

Luminous nebulae comprised of ionized hydrogen with numerous and sometimes hundreds of young stars can be seen in our own galaxy, in nearby galaxies, and in distant galaxies. These star-forming regions are sites of clusters of stars containing some massive objects that are synthesizing many of the heavy chemical elements, later to be spewed out in stellar explosions. Studies of these objects with Hubble allowed the details of the nebulae to be mapped along with the interaction of the hot stars emitting intense ultraviolet radiation causing the nebular material to be ionized and glow. The first images of such regions included the Orion star-forming region and the Eagle Nebula.



*Image mosaic of the Orion Nebula exhibiting clumps of stars forming and the detailed sculpting of the nebula by radiation from the bright young stars formed there. (Hubble Advanced Camera for Surveys and European Southern Observatory at La Silla [Chile] 2.2-m [7.2-ft] telescope.)*

One such huge complex is 30 Doradus—the largest in the local group of galaxies. It is located 170,000 light-years from Earth in the Large Magellanic Cloud, a companion galaxy to the Milky Way. It has been called an astronomical “Rosetta Stone” because detailed examination of the object gives a clue to the nature of star-forming regions that are seen, but unresolved, in distant galaxies across the universe.

The Orion Nebula is a star-forming region in our own galaxy and close enough to be seen in small telescopes as it is 1,500 light-years away. Because this region is so vast, the large mosaic image was created after the Advanced Camera for Surveys was installed. Detailed examination of parts of the image shows stars, gas, and dust as



*The Wide Field Planetary Camera 2 image of 30 Doradus in the Large Magellanic Cloud contains one of the most spectacular clusters of massive stars, called R136, in our cosmic neighborhood of about 25 galaxies.*

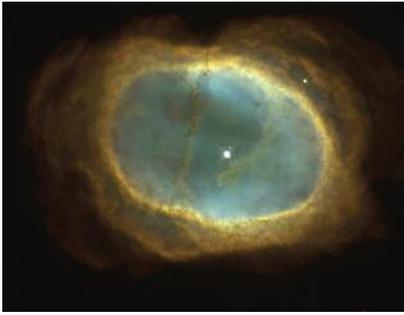
well as several regions revealing clusters of stars forming. The nebula itself is being disrupted by radiation from those stars, leaving loops, bubbles, and rings of material, all of which can be distinguished with the high-resolution Advanced Camera for Surveys composite.

With the installation of the infrared Wide Field Camera 3 during servicing mission 4, Hubble observers can peer into the dust of these tumultuous regions.

## Stellar Death Throes

### Planetary Nebulae

Some of the most photogenic nebulae are remnants of the last stages of stellar life, called planetary nebulae. These nebulae are formed from stars with mass similar to the sun while stars larger than eight times the solar mass end as supernovae. In small telescopes, these nebulae appear as roundish, smooth objects but, in fact, no two planetary nebulae are alike. With Hubble observations, it has become clear that planetary nebulae formation is very complex. Material is often ejected in rings and loops, and the nebulae chaotic structures suggest that these stars shed mass in several



*The diversity of planetary nebulae is shown in this image. The nearly symmetric appearance of NGC 3132 in this Wide Field Planetary Camera 2 image shows the more “classic” morphology of a planetary nebula.*



*This nebula, called NGC 6543 or the Cat's Eye Nebula, was one of the first planetary nebulae to be discovered. The Advanced Camera for Surveys image shows how complex these objects can be. Planetary nebulae exhibit a huge range of diverse morphologies due to their formation process.*

episodes. Some of the nebulae exhibit irregular streamers and nodules as well. It is likely that the interplay of stellar winds and radiation emitted by the star causes the structures, but the exact manner in which this occurs is still poorly understood.

### **Supernovae and Supernova 1987A**

Stars larger than about eight times the mass of the sun end their lives in a different, spectacular way as their nuclear fuel is exhausted. The violent explosion, a supernova, blows off a significant fraction of the star's mass into a nebula or remnant, emitting radiation from the x-ray to the radio.

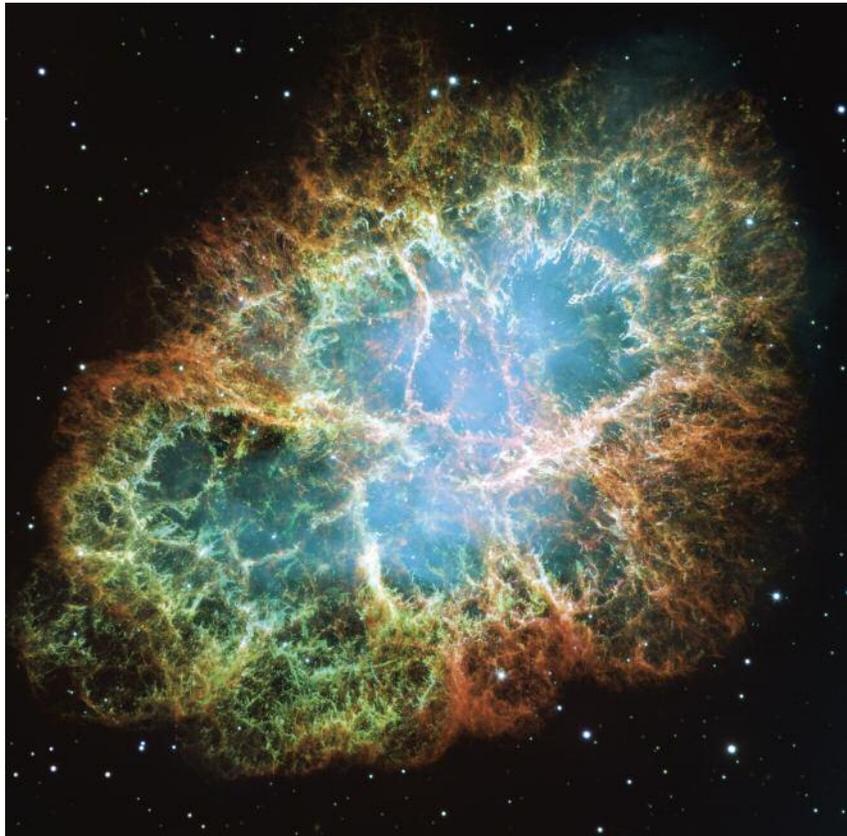
The resulting nebula is a complex twist of material and magnetic fields, giving these objects complicated shapes. The detailed, exceptional imagery from Hubble has allowed researchers to examine the morphologies of these objects.

There are several classifications of supernova reflecting different features and formation mechanisms. The supernovae called type Ia are sometimes formed by binary stars. The importance of these types of supernova is that they appear to have a signature luminosity increase and a particular relationship between the various energies emitted. Because they have unique characteristics, they are considered “standard candles”; i.e., they have a known intrinsic brightness

so that, when they are discovered in distant galaxies, the distance to them can be fairly accurately determined. These objects are lynchpins in the study of the expansion of the universe and the discovery of dark energy.

One well-known supernova in our own galaxy, the Crab Nebula, has been imaged by Hubble over several years. In addition to the intricate appearance of the nebula, the actual explosive event was witnessed by Japanese and Chinese astronomers in 1054 and most likely was also seen by Native Americans.

Many supernovae remnants in the galaxy are so large they cannot be imaged easily with a few exposures of Hubble. The supernova remnant called N132D is one of several such objects imaged by Hubble. It is located in

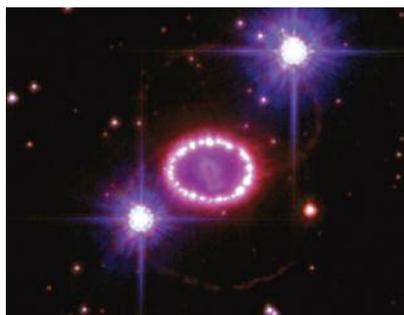
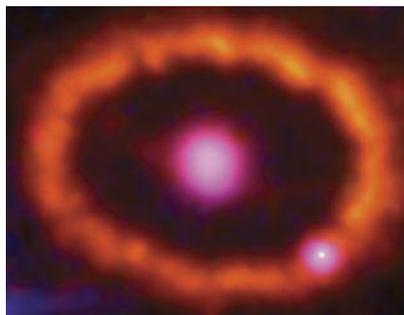
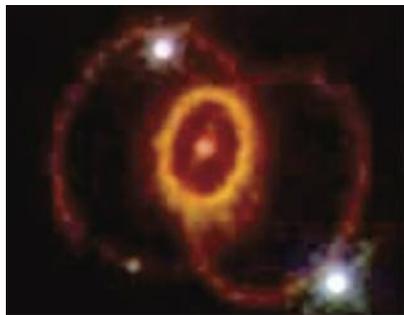


*A giant mosaic of Wide Field Planetary Camera 2 observations of the Crab Nebula, compiled from observations accumulated in 1999 and 2000.*



*This Advanced Camera for Surveys and Wide Field Camera 3 image is of supernova remnant N132D in the Large Magellanic Cloud.*

*Light from the explosion illuminated the remnant material around supernova 1987A. The Wide Field Planetary Camera 2 images revealed an hourglass structure evidenced in the two overlapping rings. The central ring is apparently in a plane parallel to the other rings, which are in front of and behind the central ring as seen from this vantage point. The upper image was obtained in 1994. The next image, also obtained in 1994, shows the brightening of the inner ring caused by the explosion shockwave impacting the ring. Twenty years after the explosion, Hubble was able to resolve multiple sites that were illuminated due to the shockwave continuing to expand outward into the remnant material from prior events. The lower image, from Advanced Camera for Surveys, shows the fully illuminated ring and the outer ring structure from 2006.*



the Large Magellanic Cloud, close enough for detailed examination, but sufficiently far away to allow the whole structure of the nebula to be examined. The observation of N132D is actually a composite of the newly restored Advanced Camera for Surveys, repaired during servicing mission 4, and the new Wide Field Camera 3. A spectrum of this object was also obtained with the new Cosmic Origins Spectrograph instrument to analyze the chemical composition of the nebula.

The most famous and scientifically important supernova is supernova 1987A, an object that exploded in the Large Magellanic Cloud in February 1987. The light from the explosion expanded outward and illuminated material far from the progenitor star, suggesting prior outflows and explosions may have occurred. Astronomers have used nearly every Hubble camera to monitor changes in supernova 1987A. Merged with observations from other observatories, the Hubble images have contributed to the understanding of this particular object. This information also has helped with understanding of type Ia supernovae in general.

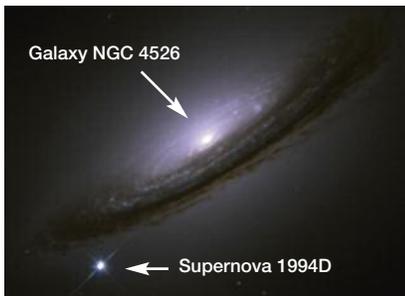
### **Dark Energy**

At its inception, Hubble was designed to determine the age of the universe through measurements of cosmological expansion—the value of Hubble constant. Every improvement in instrumentation, computing systems, and telescope capability has led to greater knowledge and sometimes extraordinary results about the cosmos. As details of the universe’s expansion unfolded, astronomers derived an unexpected nuance of the expansion. It appears from Hubble observations that the universe is not expanding

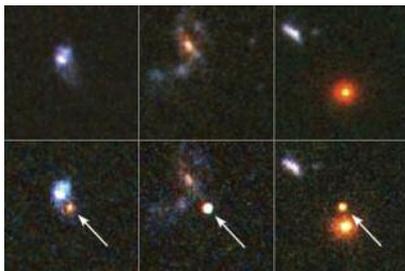


at a constant rate or slowing down under the tug of gravity as astronomers expected. Instead its expansion is speeding up and has been for the past 4 to 5 billion years.

A key to this discovery is the understanding that, like Cepheid variables, supernovae can be used as distant light posts or standard candles, but supernovae are about a million times brighter. One type of supernova explosion, a *Type Ia Supernova* (abbreviated SN Ia), is thought to explode as a result of binary stars exchanging matter. The explosive output,  $1-2 \times 10^{44}$  joules or about  $3.5 \times 10^{28}$  megatons of TNT, has a specific profile: a fast rise in a few hours or days and a decline over about a month or so. These objects also achieve a more or less typical intrinsic brightness—the characteristic that makes SN Ia a valuable standard for measuring the distances to its very remote host galaxies in which the supernova is imbedded.



*Supernova 1994D in galaxy NGC 4526 can be seen as the bright star in the lower left corner of this Hubble Wide Field Planetary Camera 2 image.*



*Images of three of the most-distant supernovae known, discovered using the Advanced Camera for Surveys.*

**Steven Hawley, PhD**

*Astronaut on STS-41D (1984), STS-61C (1986), STS-31 (1990), STS-82 (1997), and STS-93 (1999).*



*“I have been very fortunate to be among a very small group of individuals to have seen the Hubble Space Telescope in space—twice. A memory that I will cherish forever is seeing the Hubble Space Telescope as we approached on STS-82, 7 years after I released it from Discovery in April 1990. To see Hubble Space Telescope once in a career is special, but to see it twice is truly a privilege. I remember when we were able to see the back side of Hubble Space Telescope for the first time on the 1997 mission. Hubble Space Telescope keeps one side preferentially pointed at the sun and that side is opposite the side to which you approach in the shuttle to grapple the telescope. When we saw the far side, we were able to see that the thermal insulation resembling aluminum foil looked brittle and had peeled away from the telescope in some locations. Prior to the last extravehicular activity for that mission our crew was asked to fabricate some temporary patches from material that we had on board and to install them over some of the worst damaged sites. Before we did that we all signed the foil patches, so for a while my signature was on the Hubble Space Telescope.”*

Hubble was employed along with several powerful ground-based telescopes to seek out and measure SN Ia across the universe. Hubble Wide Field Planetary Camera 2 was first used to map SN Ia and then deep Advanced Camera for Surveys observations probed the most distant supernova. The amassed observations helped refine Hubble constant. Since the measurements extended to some of the farthest reaches of the universe, it was possible to use all the SN Ia observations pieced together to measure another important cosmological

parameter: the cosmological constant. The cosmological constant was proposed by Einstein in his General Relativity as a kind of “repulsive gravity,” a means of keeping the universe static so that it would not collapse under its own gravity. When he learned from Edwin Hubble that the universe is not static but is in fact expanding, Einstein removed the cosmological constant from his equations (and referred to it as “my greatest blunder”). The observations by the Hubble Space Telescope and its partner ground-based telescopes that



the expansion of the universe is in fact accelerating under the influence of some completely baffling force, a kind of repulsive gravity, strongly suggests that the cosmological constant may not have been a “blunder” after all.

This result is problematic as we currently do not have a succinct theory to explain why this situation exists. For example, we know the Big Bang that originated the universe causes objects to recede from each other when measured over cosmological distances. We also know that gravity is the retarding force that slows the expansion due to mutual attraction between all matter in the universe. Therefore, either the universe would keep expanding because there is not enough matter (gravity) to slow it or its expansion would slow (decelerate) because there is enough gravitational force to retard that expansion. Acceleration of the expansion does not fit into this picture. The unexplained cause of the acceleration, called dark energy, is the focus of additional observations and theoretical work. The existence of the acceleration has been confirmed by detailed analysis of the Wilkinson Microwave Anisotropy Probe observations designed to measure the cosmic microwave background, the remnant radiation from the Big Bang. Other observations of x-ray emission, further observations of supernovae, and other results have contributed to the confirmation of this puzzle.

Needless to say, the discovery of evidence for dark energy was not predicted for Hubble or for any other observatory constructed to date. This significant problem in physics and astrophysics is expected to be a driving part of the design for new telescopes to be commissioned in the next decade.



*This is an image of a gravitational lens obtained after servicing mission 4 with the newly repaired Advanced Camera for Surveys camera. Abell 370 is one of the very first galaxy clusters where astronomers observed the phenomenon of gravitational lensing.*

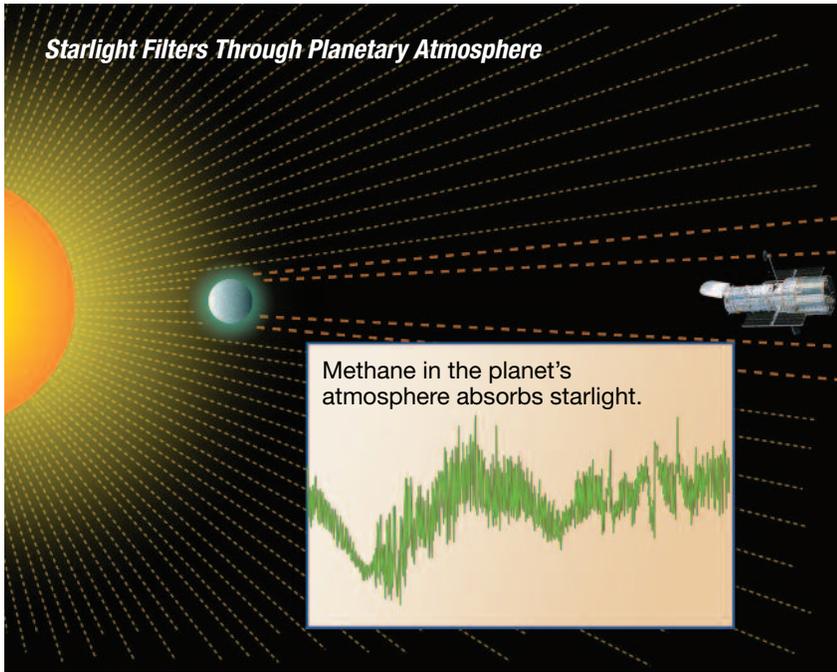
### **Dark Matter**

An interesting phenomena produced by gravitational fields is *gravitational lensing*. A warping of space by a large mass such as a cluster of galaxies can distort light from more distant objects. The distortions appear as shreds of images, stretched into arcs and streaks. Gravitational lenses are of interest for two main reasons: first, the very distant objects can be analyzed since the lens also enhances the brightness of the far galaxy or luminous quasar; and second, the total mass of the lensing cluster can be determined. The total mass is a composite of luminous mass (the galaxies detected by Hubble) plus dark, unseen matter. Reconstruction of the mass distribution gives clues to the nature of dark matter that cannot be seen through telescopes. Such observations also were combined and used to create a three-dimensional

map of dark matter in the universe, although the true nature of the material is still unknown.

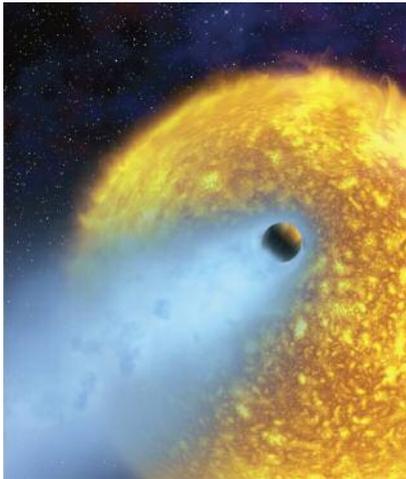
### **Extrasolar Planets**

A planet outside the solar system is commonly categorized as an extrasolar planet. Scientists have made confirmed detections of 473 such planets. The vast majority were detected through velocity calculations observations and other indirect methods rather than actual imaging. The search for planets forming around other stars has been a consistent theme in research conducted with Hubble. Besides probing star-formation regions, Hubble is used to detect planetary disks around stars where planets are likely to be forming. While it was not expected that Hubble would contribute significantly to the detection and characterization of extrasolar planets, the opposite has been true.



An illustration of the spectrum obtained from an extrasolar planet and the configuration of the parent star, the planet, and Hubble to obtain the observation.

In 2001, Hubble observed the first transit of an extrasolar planet across the disk of its parent star. The yellow dwarf star HD 209458 has a



Scientists reported the first-ever optical detection of an extrasolar planet, which passed in front of a huge star in the constellation Pegasus. This transit dimmed the light of the star by a measurable 1.7%. This shows the capability of Hubble to detect extrasolar planets.

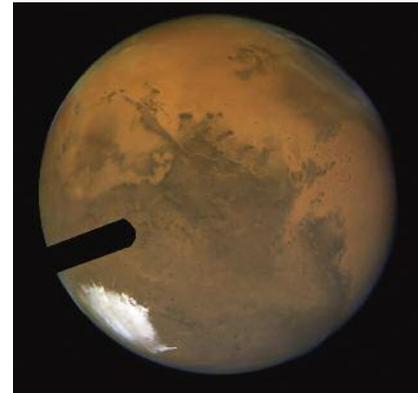
Jupiter-sized planet in a tight, 3½-day orbit around it. The extremely close orbit causes the planet to lose its atmosphere; i.e., the atmosphere is blowing off its surface into space. It is the planet plus the atmospheric material that caused a slight dip in the brightness of the star that could be observed with precise observations.

In 2007, Hubble actually detected the atmosphere of an extrasolar planet, a new achievement in planetary research. The light from the star passed through the atmosphere of the planet and was detected by Hubble's Near Infrared Camera and Multi-Object Spectrometer. The atmosphere contains methane, carbon dioxide, carbon monoxide, and water molecules. This exciting observation was an important achievement because it demonstrated that prebiotic materials are present in

the atmosphere of at least one extrasolar planet, and that as such measurements are possible with Hubble they bode a bright future for such research with the James Webb Telescope.

### Solar System

Hubble has not been idle in contributing to the understanding of our solar system objects. The first spectacular solar system observation was that of the 1994 crash of Comet Shoemaker-Levy 9 into Jupiter. Subsequently, Mars is and has been actively researched with Hubble. Wide Field Planetary Camera 2, Near Infrared Camera and Multi-Object Spectrometer, Space Telescope Imaging Spectrograph, and Advanced Camera for Surveys have all monitored weather conditions, observed seasonal changes, mapped the polar caps, watched dust storms, and conducted remote "site surveys" of landing spots for Martian probes. In the Advanced Camera for Surveys image of the sharpest Earth-based image ever taken of Mars, small craters and other surface markings only about a few tens of kilometers (a dozen



An Advanced Camera for Surveys image of Mars exhibiting the sharpest view ever taken from Earth. In view are numerous craters, several large volcanoes of the great Tharsis plateau along the upper left limb, and a large multi-ring impact basin, called Argyre, near image center. There is a reddish tinge over the southern ice cap suggesting dust contamination in the clouds or the ground ice.



miles) across can be seen. Hubble continues to support the NASA Mars mission and probe activities.

Other phenomena observed include the changing atmosphere of Jupiter, spectacular views of Jupiter's moons, the rings of Saturn in various phases, an aurora on Uranus, clouds on Neptune, and the first map of the surface features of Pluto. Hubble observations contributed to the characterization of asteroids and support of NASA probes landing on such objects, discovery of outer solar system Kuiper belt objects, and measurements of Quaoar and the dwarf planet Eris. The latter observations, in concert with data from the W.M. Keck Observatory in Hawaii, helped lead to the reclassification of Pluto as a "dwarf planet."

### Most Popular Results

In addition to extensive research results obtained through the use of Hubble observations, public enthusiasm for NASA's endeavors—and Hubble in particular—is a consequence of the open and active press release system for Hubble.

Public understanding of astronomy and somewhat of science in general comes from the free availability of Hubble results. Particular images become popular by nature of their image quality, such as nebulae and galaxies. Other images are fascinating due to the astrophysical processes they depict, such as extrasolar planets, the distant universe, and Mars. Many images are also used in education to improve science literacy. All Hubble press release material can be found at: <http://hubblesite.org/newscenter/archive/releases/YEAR/PR>.

## Hubble Scorecard

The initial primary driver for Hubble was cosmological studies; specifically, the determination of the age of the universe. Other important research areas involved the nature of galaxies and black holes, and the details of the intervening material permeating the universe. Below are a few examples of the anticipated and unanticipated science results. The qualities of Hubble, such as diffraction limited, high-sensitivity imagery, excellent spectroscopic capability, and high-contrast imaging from the ultraviolet through the visible to the infrared has provided for the exemplary science achieved.

### Anticipated science:

- Measurement of the expansion rate of the universe since the Big Bang
- Confirmation of the existence of massive black holes in galaxies and a census of less-massive black holes in smaller galaxies and black holes in binary star systems
- Observation of emission revealing the physical nature of energetic active galactic nuclei
- Discovery of the host galaxies associated with enigmatic quasi-stellar objects (quasars)
- Detection of the intergalactic medium and the interstellar medium through absorption of light from distant quasars

### Unanticipated science:

- Characterization of conditions for galaxy formation in the early universe through mergers and black hole formation
- Detection of the acceleration of the universe corresponding to the discovery of dark energy, the cosmic mechanism that counteracts the slowdown of the universe caused by gravity
- Unveiling the nature of gamma-ray bursts through identification of the host galaxies
- Observations of planetary disk formation
- Detection of extrasolar planets and several atmospheres of planets orbiting other stars

### Other Science and Technology

The development of Hubble and its relationship to the shuttle, as well as other NASA programs, yielded advances in science and technology beyond discoveries about the universe. The advancement of optical and infrared detectors for use in space and the evolution of various sensors, circuitry, and navigation systems are all part of the contribution toward technologies

needed to support the science and instrumentation. Other benefits of the program include the manufacture of robust electronic chips, hard drives, computation systems, and software. The science and technology required for human and robotic space exploration transformed due to the partnership between the Hubble science endeavor and the Space Shuttle Program.



## Compton Gamma Ray Observatory

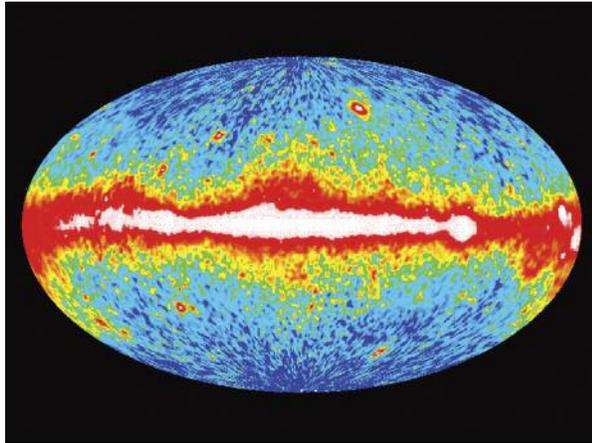
Hubble was the first Great Observatory, while Compton Gamma Ray Observatory was the second. Its launch on Space Shuttle Atlantis (Space Transportation System [STS]-37) in 1991 represented a benchmark in shuttle lift capability since it was the heaviest astrophysical payload flown to date. As planned, Compton spent almost a decade enabling insight into the nature and origin of enigmatic gamma-ray sources and was safely deorbited and reentered the Earth's atmosphere on June 4, 2000. The observatory was named in honor of Nobel Prize winner Dr. Arthur Compton for his physics research on scattering of high-energy photons by electrons, a critical process in the detection of gamma rays.



*Compton Gamma Ray Observatory being prepared for deployment from Atlantis, STS-37 (1991).*

### Instrumentation

Compton was designed to detect high-energy gamma-ray emissions caused by diverse astrophysical phenomena including solar flares, pulsars, nova and supernova explosions, black holes accreting material, quasars, and the bombardment of the interstellar medium by cosmic rays. Four scientific instruments—Burst and Transient Source Experiment, Oriented Scintillation Spectrometer Experiment, Imaging



*Can you imagine “seeing” gamma rays? This computer-processed image allows you to “see” the entire sky at photon energies above 100 million electron volts. These gamma-ray photons are 10,000 times more energetic than visible-light photons and are blocked from reaching Earth’s surface by the atmosphere. A diffuse gamma-ray glow from the plane of our Milky Way is seen across the middle belt in this image.*

Compton Telescope, and Energetic Gamma Ray Experiment Telescope—were intended to cover the high end of the electromagnetic spectrum.

While previous gamma-ray missions sampled astrophysical sources (after the original chance detection of gamma rays by the Vela military satellite in the 1960s), Compton pushed to a factor of 10 sensitivity improvement in each instrument. Based on the spectacular results, specifications emerged for new gamma-ray satellites.

### Compton Science Results

All-sky surveys are an important tool for uniformly mapping the sky and understanding the overall relationship of various components of the nearby neighborhood as well as the universe. The Energetic Gamma Ray Experiment Telescope instrument provided a high-energy map that demonstrated the interaction between the interstellar gas that pervades the disk of our galaxy with cosmic rays. The telescope also sampled variable extragalactic sources such as quasars that emit in high-energy “blazers.”

All-sky maps also were obtained with the Imaging Compton Telescope and Oriented Scintillation Spectrometer

Experiment. The Imaging Compton Telescope surveyed a narrow energy band of gamma rays. It also detected neutrons from a solar flare early on in the program. The Oriented Scintillation Spectrometer Experiment survey mapped the center of our galaxy and was also sensitive to solar flares caused by accelerating particles colliding with the sun’s surface.

The workhorse of the Compton observatory was the Burst and Transient Source Experiment, designed to detect gamma-ray bursts. The first result was to confirm that the bursts came from all over the sky, suggesting a cosmic origin rather than a local solar neighborhood cause or some phenomena restricted to our galaxy. The brief flashes were eventually traced to chaotic events, some associated with the collapse of stars in distant galaxies. The instrument also detected gamma-ray burst repeaters and a few sources that were identified by monitoring x-ray sources and watching them wink out as the Earth occulted the object. These discoveries began to narrow in on the types of phenomena that could produce gamma rays.

Compton ended its impressive science career in 1999 with a gyro failure. A safe re-entry into Earth’s atmosphere was successfully executed in 2000.

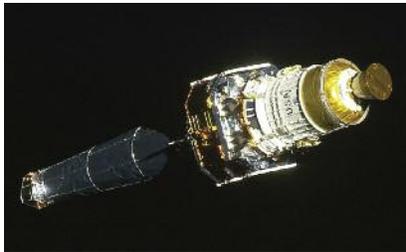


## The Chandra X-ray Observatory

NASA named its x-ray observatory to honor the scientific achievements of American Astrophysicist Dr. Subrahmanyan Chandrasekhar who was awarded the Nobel Prize in Physics (1983) for his theoretical studies of the physical processes of importance to the structure and evolution of the stars.

X-rays are emitted by a plethora of objects including galaxies, exploding stars, black holes, and the sun.

The Chandra X-ray Observatory was designed to probe x-ray emitters across the universe. When Chandra was deployed from Space Shuttle Columbia—Space Transportation System (STS)-93 (1999)—it was the longest satellite and provided a new heaviest-science-payload benchmark. Chandra is the third Great Observatory launched by NASA.



*Chandra X-ray Observatory.*

### Scientific Research with Chandra

Chandra detected many types of sources, but the nature of black holes definitely caught the attention of both the scientific community and the public. Even in our own locale, the black hole at the inner 10 light-years of our galaxy was mapped. This source emits x-rays due to the extremely hot temperature

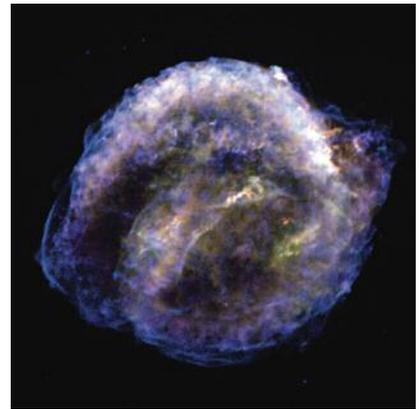
(millions of degrees) of the material that has been gravitationally captured by the black hole and is spiraling into it. Chandra detected a “cool” black hole at the center of the Andromeda Galaxy, and more black holes were found that were confirmed as “supermassive” black holes in other galaxies.

Chandra data on individual stars have shown that binary star systems in collapse can produce x-rays, and normal stars in formation can produce x-rays through their stellar winds. Chandra showed that nearly all normal stars on the main sequence emit x-rays.

Chandra also provided a gallery of observations of supernova remnants. Research allowed scientists to understand how some supernovae are produced by binary stars, and how remnant neutron stars and pulsars interact with their surroundings. The dynamic of the shock wave, interactions with the interstellar medium, and the origin of cosmic rays are all in evidence in the x-ray emissions. The detailed compositions and distribution of the ejecta are traced in the x-rays.

Chandra also provided insight into the “hard x-ray” background—energies in the 2-10 keV range was a mystery for several decades. Some of these sources appear to be quasars as expected, and others are associated with nuclei of active galaxies that are fainter and possibly obscured by surrounding dusty material.

Observations of the “deep fields”—the Hubble Deep Fields and also the fields selected to survey deep x-ray emission—bolster the idea that some sources are quasars and active galaxies. The supermassive black holes in these objects cause intense x-rays to be emitted. Other distinct sources are galaxies with modest x-ray luminosity.



*The Chandra image of one of the youngest supernova remnants in the galaxy, Kepler's supernova. This remnant may have been produced by the collapse of a single star relatively early in its lifetime.*

Gamma-ray bursts were mysterious sources. Once the gamma ray is detected, rapid scheduling of telescopes allows the observation of the afterglow, including in the x-ray. Chandra data can assist in the determination of the elements present near the object.

The combined observations of optical, infrared, and x-ray emission from clusters of galaxies led to the identification of dark matter. It is suspected that most of the universe is filled with dark matter and the luminous material represents a few percent of the universe's contents. Observations of several clusters of galaxies showed that the collision of these massive clusters left a clump of dark matter behind. This implies that dark matter is not exactly the same as the luminous material seen in optical images of the galaxies in the clusters. The material left behind also produces impressive gravitational lensing of more distant objects. What dark matter is exactly remains a mystery.



### **Eileen Collins**

*Colonel, US Air Force (retired).  
NASA's first woman Space Shuttle pilot and commander.  
Pilot on STS-63 (1995) and STS-84 (1997).  
Commander on STS-93 (1999) and STS-114 (2005).*

### **The Chandra X-ray Observatory: One of the shuttle's many success stories**

*"On July 23, 1999, I had the incredible privilege of commanding the Space Shuttle Columbia, which took the Chandra X-ray Observatory into space.*

*"Some fun facts about Chandra: the observatory can focus so well it could read a newspaper at half a mile. If the surface of the Earth was as smooth as Chandra's mirrors, the highest mountain would be no greater than 1.8 m (6 ft) tall.*

*"STS-93 was a dream mission for me. Not only did I have an opportunity to command a shuttle mission, I could marry it with a longtime hobby: astronomy. When I was a child in Upstate New York, I would look to the stars at night and feel inspired and excited. I wanted to travel to each one of those points of light, know what was there, what were they made of. Were there people there?*

*"I moved to Oklahoma for US Air Force pilot training. The wide open, dark, clear skies encouraged me to buy my first telescope. I bought books and magazines on astronomy and spent most of my spare time reading! Many shuttle astronauts came to Vance Air Force Base for training. This combination of exposure to the night skies and the emerging Space Shuttle Program inspired me to plan my career around my eventual application to the astronaut program!*

*"After over a year of training for STS-93 and several unexpected launch delays, my crew headed to the launch pad on July 20, 1999, which coincided with the 30th anniversary of Apollo 11. Our launch was manually halted at T minus 8 seconds by a sharp engineer who saw the 'hydrogen spike' in the aft compartment. A sensor had failed, and we were subsequently cleared to launch again in 2 days. After a single weather scrub, we rescheduled for the 23rd and lit up the*



*sky shortly after midnight. Well, this was no ordinary launch! Five seconds after liftoff, we saw a 'Fuel Cell pH' message, received a call from Houston about an electrical short, which took out two main engine controllers! Unbeknownst to us, there was a second problem: at start-up, a pin had popped loose from a main engine injector plate. It hit several cooling tubes, causing us to leak hydrogen. Due to the shuttle redundancy and robustness of the main engines, they did not fail. The shuttle fleet was grounded to conduct thorough wiring inspections, resulting in many lessons learned for aging spacecraft.*

*"Despite the launch issues, I believe it was the right decision to launch Chandra on the shuttle vs. an expendable launch vehicle. The mission reaped the benefits of a human presence. True, a shuttle launch is more costly, but it is similar to buying insurance for missions with irreplaceable payloads.*

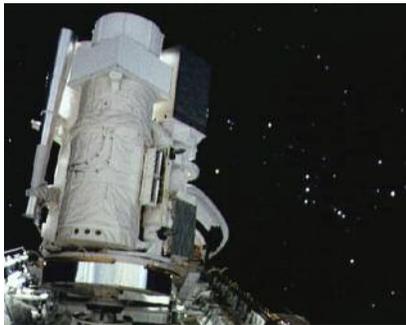
*"Today, the Chandra X-ray Observatory is increasing our understanding of the origin, evolution, and destiny of the universe. It is an incredible product of human ingenuity. The data will be around for generations of worldwide scientists to digest as we discover our place in the universe. I see Chandra as an expression of our curiosity as humans. As we search to discover what makes up this wondrous universe we live in, creations like Chandra will be far and away worth the investment we put into them. Chandra is one of the successful, productive, and mighty success stories of the Space Shuttle Program!"*



## Other Space Science Missions

### Ultraviolet Programs

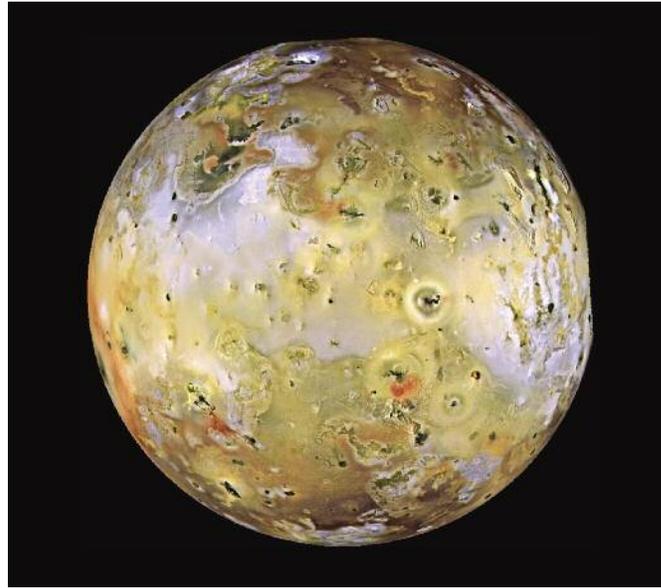
NASA devoted two shuttle flights to instrument packages designed to study the ultraviolet universe. A pallet of telescopes called the “Astro Observatory” were mounted together to fly several times. Astro-1 comprised three ultraviolet telescopes and an x-ray telescope while Astro-2 concentrated on the ultraviolet. Astro-1 flew on Columbia—Space Transportation System (STS)-35 (1990)—and Astro-2 flew on Endeavour—STS-67 (1995). The missions were designed to probe objects in the solar system, our galaxy, and beyond. Data on supernovae such as the Crab Nebula, planetary nebula, globular clusters, and young stellar disks were obtained.



*Space Shuttle Columbia (STS-35) carries Astro-1 for observations of the ultraviolet universe in December 1990.*

### Exploring Stellar Surfaces: Hot and Cold Stars

The Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer Shuttle Pallet Satellite missions were designed to be free-flying missions



*Image of Jupiter's moon Io obtained with the Galileo spacecraft. Io has the most volcanic activity in the solar system, giving it this mottled appearance. Features down to 2.5 km (1.6 miles) in size are seen along with mountains, volcanic craters, and impact craters from asteroids and comets.*

supported by the shuttle. Space Shuttle Discovery (STS-51) deployed this satellite in 1993, the first of a series of missions. Ultraviolet spectra of hot stars, the coronae of cool stars, and the interstellar medium were observed. The second mission observed nearly 150 astronomical targets including the moon, nearby and more distant stars in the Milky Way, other galaxies, a few active galaxies, and the energetic quasar 3C273.

### Chasing Jupiter and Its Moons

NASA's Galileo Mission was designed to study Jupiter and its system of moons. The spacecraft was launched by Space Shuttle Atlantis (STS-34) in 1989. Galileo was fitted with a solid-fuel upper stage that accelerated the spacecraft out of Earth orbit toward Venus. Galileo arrived at Jupiter and entered orbit in December 1995.

The spacecraft orbited through the Jovian system, measuring the moons as well as the planet Jupiter. Galileo sent a probe into Jupiter's atmosphere, finding the planet's composition to differ from that of the sun—important for understanding how the solar system formed. It provided the first close-up views of the large moons—Io, Europa, Ganymede, and Callisto—showing the dynamic Io volcanic activity and evidence that Europa may have a frozen surface with liquid underneath. Discoveries of many new moons around Jupiter, flybys of asteroids, and an interaction with a comet are part of Galileo's accomplishments. The spacecraft also was fortuitously in position to image the full sequence of more than 20 fragments of Comet Shoemaker-Levy impacting Jupiter in 1994.

The Galileo mission ended on September 21, 2003, when the spacecraft plummeted into Jupiter's atmosphere. From launch to impact, Galileo



traversed trillions of kilometers (miles) on a single tank of gas, not counting the fuel for the shuttle. The total amount of data returned during its 14-year lifetime was 30 gigabytes, including 14,000 memorable pictures.

## Studying the Anatomy of the Sun

On February 14, 1980, NASA launched the Solar Maximum Satellite (SolarMax) aimed at studying the maximum part of the sun's cycle. During this intense period, the sun's surface activity is characterized by massive ejections of high-energy particles extending into the solar system. SolarMax's life was almost cut short by a malfunction, but it fortunately was extended due to servicing by Space Shuttle Challenger (STS-41C) in 1984. Astronauts performed maintenance and repairs by replacing the attitude control system and one of the main electronics boxes, demonstrating that satellites could be repaired successfully and given extended life when serviced by the shuttle. SolarMax's career ended with re-entry on December 2, 1989.

The SolarMax instruments were mainly designed to study the x-ray and gamma-ray emissions from the sun. Two of the instruments also were capable of observing celestial sources outside the solar system. Observations showed that due to the bright faculae in the vicinity of dark sunspots are so intense that they increase the overall brightness of the sun. Therefore, the sun not only emits many charged particles but is also more intense during sunspot maximum.

## The Magellan Mission: Mapping Venus

The Magellan spacecraft was launched on May 4, 1989, by Space Shuttle Atlantis from Kennedy Space Center, Florida, arrived at Venus on August 10, 1990, and was inserted into a near-polar elliptical orbit. Radio contact with Magellan was lost on October 12, 1994. At the completion of radar mapping, 98% of the surface of Venus was imaged at resolutions better than 100 m (328 ft), and many areas were imaged multiple times. The Magellan mission scientific objectives were to study land forms and tectonics, impact processes, erosion, deposition, and chemical processes and to model the interior of Venus. Magellan showed us an Earth-sized planet with no evidence of Earth-like plate tectonics.

## Our Amazing Star: The Ulysses Mission

To fully understand our amazing star, it was necessary to study the sun at near maximum conditions. During the solar maximum, Ulysses reached the maximum Southern latitude of our sun on November 27, 2000, and traveled through the High Northern latitude September through December 2001.

After more than 12 years in flight, Ulysses had returned a wealth of data that led to a much broader understanding of the global structure of the sun's environment—the heliosphere.

## Summary

Many hundreds of years ago, our ancestors came out of their caves, gazed at the stars in the sky, and wondered, "How did we get here?" and "Are we alone?" They likely asked themselves, "Is there more out there?" and "How did this world begin?" They tried to comprehend their place in this complex puzzle between the Earth and the skies. We live in an age that has seen an explosion of science and technology and the beginnings of space exploration. We are still asking the same questions.

The Space Shuttle played a significant role in leading us toward some of the answers. Space science missions discussed here are opening a new window on our universe and providing a glimpse of galaxies far beyond.

Clearly, the partnership between the Space Shuttle Program and the Hubble Space Telescope, as well as other missions, contributed to the science productivity and outstanding reputation of NASA as a science-enabling agency. The obstacles that faced NASA throughout the journey were actually stepping-stones that led to a higher level of understanding not only of the universe, but of our own capabilities as a space agency and as individuals.

*"...and measure every wand'ring planet's course,*

*Still climbing after knowledge infinite..."*

— Christopher Marlowe



# Atmospheric Observations and Earth Imaging

## **Introduction**

Jack Kaye

Kamlesh Lulla

## **The Space Shuttle as a Laboratory for Instrumentation and Calibration**

### **Ozone Calibration Experiments**

Ernest Hilsenrath

Richard McPeters

### **Understanding the Chemistry of the Air**

Jack Kaye

### **Aerosols in the Atmosphere**

Zev Levin

## **The Space Shuttle as an Engineering Test Bed**

### **Lidar In-space Technology Experiment**

Patrick McCormick

## **A National Treasure—Space Shuttle-based Earth Imagery**

Kamlesh Lulla

*Earth is a dynamic, living oasis in the desolation of space. The land, oceans, and air interact in complex ways to give our planet a unique set of life-supporting environmental resources not yet found in any other part of our solar system. By understanding our planet, we can protect vital aspects, especially those that protect life and affect weather patterns. The shuttle played an integral role in this process. In the mid 1980s, NASA developed a systems-based approach to studying the Earth and called it “Earth System Science” to advance the knowledge of Earth as a planet. Space-based observations, measurements, monitoring, and modeling were major focuses for this approach. The Space Shuttle was an important part of this agency-wide effort and made many unique contributions.*

*The shuttle provided a platform for the measurement of solar irradiance. By flying well above the atmosphere, its instruments could make observations without atmospheric interference. Scientists’ ability to calibrate instruments before flight, make measurements during missions, and return instruments to the laboratory after flight meant that measurements could be used to help calibrate solar-measuring instruments aboard free-flying satellites, which degrade over their time in space. The Atmospheric Laboratory for Applications and Science payload, which flew three times on the shuttle in the early 1990s, had four such instruments—two measuring total solar irradiance and two measuring solar spectral irradiance. The Shuttle Solar Backscatter Ultraviolet Instrument, which flew numerous times, also made solar spectral irradiance measurements as part of its ozone measurements.*

*The shuttle’s low-light-level payload bay video imaging led to the discovery of upper-atmosphere phenomena of transient luminous events of electrical storms called “Elves.” NASA pointed the first laser to the Earth’s atmosphere from the shuttle for the purpose of probing the particulate composition of our air. The agency used the shuttle’s many capabilities to image Earth’s surface and chronicle the rapidly changing land uses and their impact on our ecosystems.*

*“Every shuttle mission is a mission to planet Earth” was a commonly heard sentiment from scientists involved in Earth imaging. In addition to working with many Earth observing payloads during the course of the Space Shuttle Program, “Earth-Smart” astronauts conducted scientific observations of the Earth systems. Thus, the shuttle provided an extraordinary opportunity to look back at our own habitat from low-Earth orbit and discover our own home, one mission at a time.*



## ***The Space Shuttle as a Laboratory for Instrumentation and Calibration***

Global environmental issues such as ozone depletion were well known in the 1970s and 1980s. The ability of human by-products to reach the

stratosphere and catalytically destroy ozone posed a serious threat to the environment and life on Earth. NASA and the National Oceanic and Atmospheric Administration (NOAA) assumed responsibility for monitoring the stratospheric ozone. A national program was put into place to carefully monitor ground levels of chlorofluorocarbon and stratospheric ozone, and the shuttle experiments

became part of the overall space program to monitor ozone on a global scale. The NASA team successfully developed and demonstrated ozone-measuring methods. NOAA later took responsibility for routinely measuring ozone profiles using the Solar Backscatter Ultraviolet 2 instrument, while NASA continued to map ozone with a series of Total Ozone Mapping Satellite instruments.

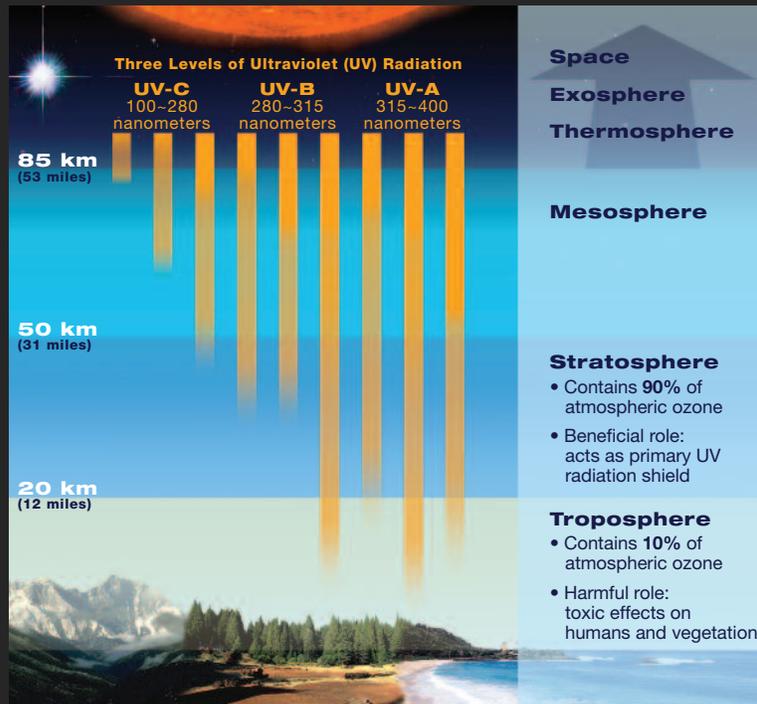
***Roles of the Space Shuttle Missions in Earth Observations***

<b>Laboratory for Calibration Instrumentation</b>	<b>Engineering Test Bed and Launch Platform</b>	<b>Earth Imaging</b>
<ul style="list-style-type: none"> <li>Shuttle Solar Backscatter Ultraviolet Instrument and Experiment</li> <li>Shuttle Ozone Limb Sounding Experiment</li> <li>Limb Ozone Retrieval Experiment</li> <li>Aerosol Experiments</li> </ul>	<ul style="list-style-type: none"> <li>Lidar In-space Technology Experiment</li> <li>Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere</li> <li>Earth Radiation Budget Satellite</li> <li>Upper Atmospheric Research Satellite</li> </ul>	<ul style="list-style-type: none"> <li>Optical Film Imaging</li> <li>Optical Digital Imaging</li> <li>Thermal Infrared Imaging</li> <li>Video Imaging</li> <li>High-definition Television</li> </ul>

*Some examples of multiple roles of the Space Shuttle: orbiting laboratory, engineering test bed, Earth imaging, and launch platform for several major Earth-observing systems.*

## Ozone Depletion and Its Impact— Why Research Is Important

The Earth's ozone layer provides protection from the sun's harmful radiation. The atmosphere's lower region, called the troposphere (about 20 km [12 miles]), is the sphere of almost all human activities. The next layer is the stratosphere (20 to 50 km [12 to 31 miles]), where ozone is found. The occurrence of ozone is very rare, but it plays an important role in absorbing the ultraviolet portion of the sun's radiation. Ultraviolet radiation is harmful to all forms of life. Thus, depletion in the ozone layer is a global environmental issue. Space-based measurements of ozone are crucial in understanding and mitigating this problem.



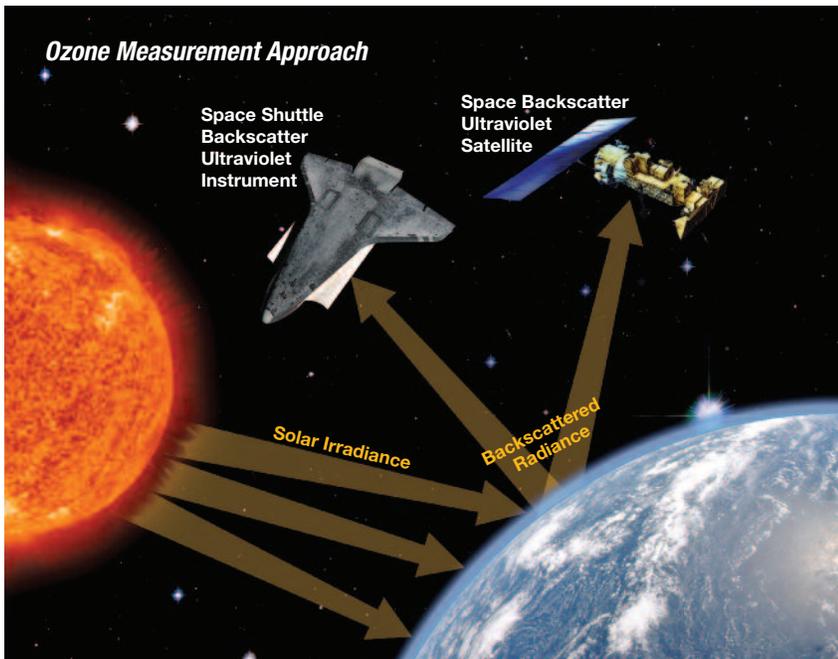
*"This most excellent canopy, the air..." wrote William Shakespeare in Hamlet long ago. The layers depicted here show the distribution of ozone. Astronauts who have viewed the layers from orbit describe it as a delicate "skin" protecting our planetary "body."*

## A Unique "Frequent Flyer" for Ozone Measurements

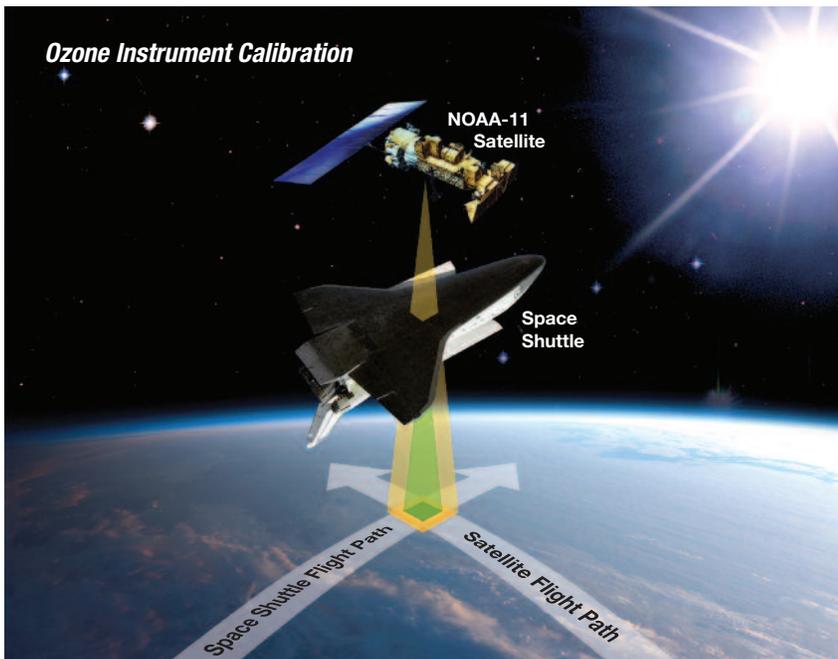
The Shuttle Solar Backscatter Ultraviolet experiment was dubbed "NASA's frequent flyer" since it flew eight times over a 7-year period (1989 to 1996)—an unprecedented opportunity for a shuttle science. Its primary mission was to provide a calibration or benchmark for concurrent ozone-monitoring instruments (Solar Backscatter Ultraviolet 2) flying on the NOAA operational polar orbiting crewless weather satellite. The NOAA satellite monitored stratospheric ozone and provided data for weather forecasts. Other satellites, such as NASA's Upper Atmosphere Research Satellite, Aura satellite, and the series of Stratospheric Aerosol and Gas Experiment and Total Ozone Mapping Spectrometer missions, measured ozone as well. Comparison of these ozone data was a high priority to achieve the most accurate ozone record needed for determining the success of internationally agreed-upon regulatory policy.

### How Did Shuttle Solar Backscatter Ultraviolet Work?

Repeated shuttle flights provided the opportunity to check the calibration of NOAA instruments with those of the Shuttle Solar Backscatter Ultraviolet instrument by comparing their observations. The shuttle instrument was carefully calibrated in the laboratory at Goddard Space Flight Center before and after each of flight.



The sun is the source of radiation reaching the atmosphere. A spacecraft carrying an ozone-measuring instrument receives the backscattered radiation. Ozone is derived from the ratio of the observed backscattered radiance to the solar irradiance in the ultraviolet region.



The National Oceanic and Atmospheric Administration (NOAA) satellite carries an ozone instrument similar to the one that flew in the shuttle payload bay. The shuttle-based instrument was carefully calibrated at Goddard Space Flight Center. The shuttle's orbital path and satellite flight pass overlapped over the same Earth location within a 1-hour window during which the measurements took place and were later analyzed by scientists.

The sun's output in the ultraviolet varies much more than the total solar irradiance, which undergoes cycles of about 11 years. Changes in ozone had to be attributed accurately from solar changes and human sources. The Shuttle Solar Backscatter Ultraviolet instrument flew along with other solar irradiance monitors manifested on Space Transportation System (STS)-45 (1992), STS-56 (1993), and STS-66 (1994). Measurements from these three Atmospheric Laboratory for Applications and Science missions were intercompared and reprocessed, resulting in an accurate ultraviolet solar spectrum that became the standard for contemporary chemistry/climate models. This spectrum was also used to correct the continuous solar measurements taken by Solar Backscatter Ultraviolet 2 on the NOAA satellite.

#### Ozone Instrument Calibrations— Success Stories

- Comparisons with NOAA-11 satellite measurements over a period of about 5 years were within 3%—a remarkable result. The key to Shuttle Solar Backscatter Ultraviolet success was the careful calibration techniques, based on National Institute of Standards developed by the NASA team at Goddard Space Flight Center. These techniques were also applied to the NOAA instruments. The shuttle was the only space platform that could provide this opportunity.



■ Although the instrument flew intermittently, it independently helped confirm ozone depletion at 45 km (28 miles), where chlorine chemistry is most active. Measurements made in October 1989 were compared with the satellite Nimbus-7 Solar Backscatter Ultraviolet measurements made in October 1980, an instrument that was also known to have an accurate calibration. Detected ozone loss of about 7% was close to predictions of the best photochemical models at that time.

■ Calibration techniques were applied to all international satellites flying similar instruments—from the European Space Agency, European Meteorological Satellite, and the Chinese National Satellite Meteorological Center—thus providing a common baseline for ozone observations from space.

#### **More Good News**

An international environmental treaty designed to protect the ozone layer by phasing out the production of a number of chemicals linked to ozone depletion was ratified in 1989 by 196 countries and became known as the Montreal Protocol. This protocol and its amendments banned the production and use of chlorofluorocarbons. Once the ban was in place, chlorofluorocarbons at ground level and their by-products in the stratosphere began going down. The latest observations from satellites and ground-based measurements indicate ozone depletion has likely ended, with good signs that ozone levels are recovering.

#### **Ellen Ochoa, PhD**

*Astronaut on STS-56 (1993), STS-66 (1994), STS-96 (1999), and STS-110 (2002).*



#### **Atmospheric Observations and Ozone Assessments**

*“The three Atmospheric Laboratory for Applications and Science missions in the early 1990s illustrated the collaborative role that the shuttle could play with unmanned science satellites. While the satellites had the advantage of staying in orbit for years at a time, providing a long-term set of measurements of ozone and chemicals related to the creation and destruction of ozone, their optics degraded over time due to interaction with ultraviolet light. The Space Shuttle carried up freshly calibrated instruments of the same design and took simultaneous measurements over a period of 9 or 10 days; the resulting data comparison provided correction factors that improved the accuracy of the satellite data and greatly increased their scientific value.*

*“One of the fortunate requirements of the mission was to videotape each sunrise and sunset for use by the principal investigator of the Fourier transform spectrometer, an instrument that used the sunlight peeking through the atmosphere as a light source in collecting chemical information. Thus, one of the crew members needed to be on the flight deck to start and stop the recordings, a job we loved as it gave us the opportunity to view the incredible change from night to day and back again. I would usually pick up our pair of gyro-stabilized binoculars and watch, fascinated, as the layers of the atmosphere changed in number and color in an incredible spectacle that repeated itself every 45 minutes as we orbited the Earth at 28,200 km per hour (17,500 miles per hour).”*

## Advancing a New Ozone Measurement Approach

From the calibration experiments conducted on five flights from 1989 to 1994, NASA expanded research on ozone elements.

The Total Ozone Mapping Spectrometer (satellite) and Solar Backscatter Ultraviolet instruments measured ozone using nadir viewing spectrometers. This approach was good for determining the spatial distribution (i.e., mapping the ozone depletion) but did a poor job of determining the vertical distribution of ozone. A spectrometer that measures light scattered from the limb of the Earth could be used for measuring how ozone varies with altitude; however, a test was needed to show that this approach would work.

While early models predicted that the largest changes in ozone as a result of the introduction of chlorofluorocarbons into the atmosphere would be observed in the upper stratosphere—in the 40- to 45-km (25- to 28-mile) region—the discovery of the ozone hole demonstrated that large changes were occurring in the lower stratosphere as a result of heterogeneous chemistry. The Solar Backscatter Ultraviolet instruments flown by NASA and NOAA were well designed to measure ozone change in the upper stratosphere.

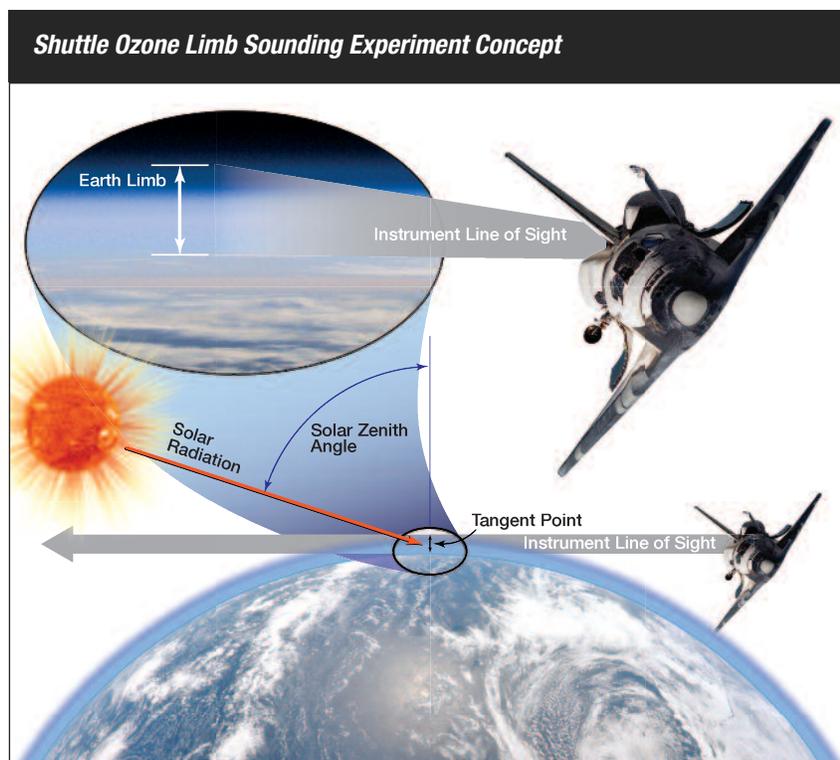
For changes occurring below 25 km (16 miles), Solar Backscatter Ultraviolet offered little information about the altitude at which the change was occurring. Occultation

instruments, such as the Stratospheric Aerosol and Gas Experiment, were capable of retrieving ozone profiles from the troposphere to nearly 60 km (37 miles) with approximately 1-km (0.6-mile) vertical resolution, but they could measure only at sunrise and sunset. Thus, the sampling limitations of occultation instruments limited the accuracy of the ozone trends derived for the lower stratosphere while the poor vertical resolution of the Solar Backscatter Ultraviolet instruments severely limited their ability to determine the altitude dependence of these trends. An instrument was needed with vertical resolution comparable to that of an occultation instrument but with coverage similar to that of a backscatter ultraviolet instrument.

The measurement of limb scattered sunlight offered the possibility of combining the best features of these two measurement approaches. The Shuttle Ozone Limb Sounding Experiment was a test of this concept.

### ***How Did the Shuttle Ozone Limb Sounding Experiment and the Limb Ozone Retrieval Experiment Work?***

To measure ozone in the upper stratosphere, scientists needed the large ozone cross sections available in the ultraviolet. To measure ozone at lower altitudes, scientists needed to use wavelengths near 600 nanometers (nm). The Shuttle Ozone Limb Sounding Experiment mission addressed these needs through the use of two



*Light scattered from the limb of the Earth is measured to determine how ozone varies with the altitude.*



instruments—the Shuttle Ozone Limb Sounding Experiment and the Limb Ozone Retrieval Experiment—flown as a single payload on STS-87 (1997).

The Shuttle Ozone Limb Sounding Experiment instrument measured ozone in the 30- to 50-km (19- to 31-mile) region. This ultraviolet imaging spectrometer produced a high-quality image of the limb of the Earth while minimizing internal scattered light.

The Limb Ozone Retrieval Experiment measured ozone in the 15- to 35-km (9- to 22-mile) region. This multi-filter imaging photometer featured bands in the visible and near infrared, and included a linear diode array detector. The 600-nm channel was the ozone-sensitive channel, the 525- and 675-nm channels were used for background aerosol subtraction, a 1,000-nm channel was used to detect aerosols, and a 345-nm channel gave overlap with the instrument and was used to determine the pointing.

#### ***New Ozone Measurement Approach Proven Successful***

Comparisons with other satellite data showed that the calibration of Shuttle Ozone Limb Sounding Experiment instrument was consistent to within 10%, demonstrating the potential of limb scattering for ozone monitoring.

This approach compared the limb ozone measurements with data from ground observations and showed that this new approach indeed worked.

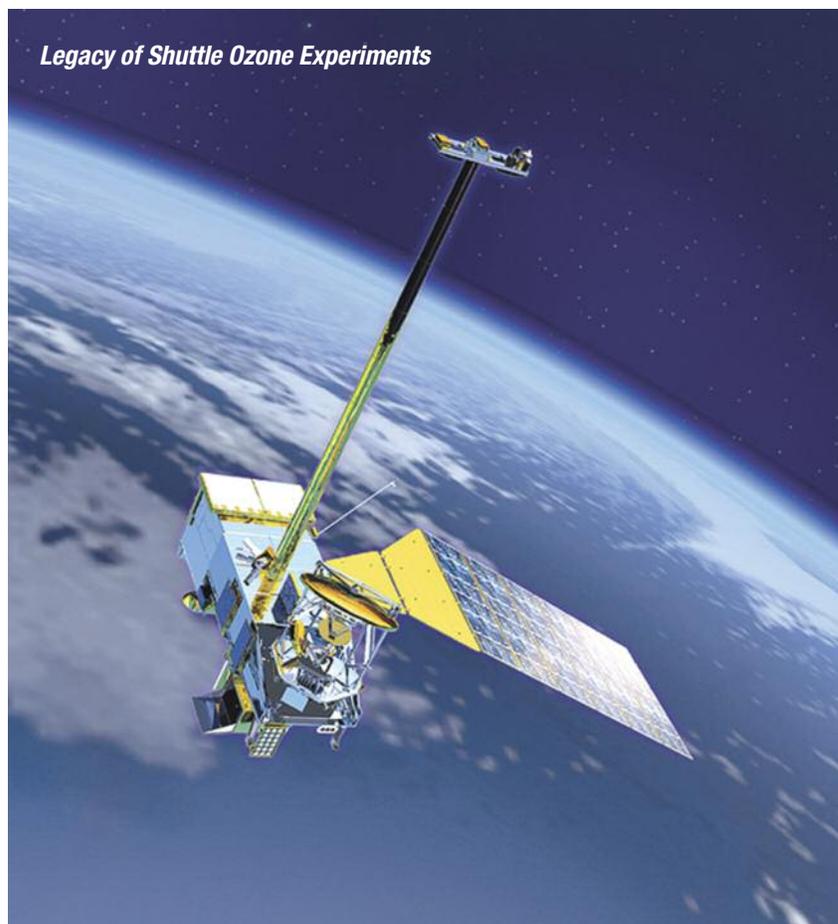
#### ***Space Shuttle Columbia's Final Contributions—Ozone Experiments***

The loss of Columbia on re-entry was a heartbreaking event for NASA and for the nation. It was a small consolation that at least some data were spared. The ozone experiments were re-flown on STS-107 (2003) to obtain limb scatter data over a wider range of latitudes and solar zenith angles with different wavelengths. For this mission, Shuttle Ozone Limb Sounding Experiment was configured to cover the wavelength range from 535 to 874 nm.

Seventy percent of the data was sent to the ground during the mission. In 2003, NASA identified an excellent coincidence between Columbia (STS-107) ozone measurement and data from an uncrewed satellite.

#### ***Summary of Ozone Calibration Research***

In all, the Space Shuttle experiments showed that limb scattering is a viable technique for monitoring the vertical distribution of ozone. On the basis of these experiments, a



*An ozone limb scatter instrument designed on the basis of successful Shuttle Ozone Limb Sounding Experiment measurements will be included in the uncrewed National Polar-orbiting Operational Environmental Satellite System. This interagency satellite system will monitor global environmental conditions and collect and disseminate data related to weather, atmosphere, oceans, land, and near-space environment.*



limb scatter instrument on a newly designed, uncrewed National Polar-orbiting Operational Environmental Satellite System has been included. This is an outstanding example of the successful legacy of these shuttle science flights.

*“The Space Shuttle is the only space platform that could provide an opportunity to calibrate the ozone monitoring instruments on orbiting satellites in order to measure ozone depletion in stratosphere. This role of Space Shuttle in ozone research has been invaluable.”*

– NASA Ozone Processing Team

## Understanding the Chemistry of the Air

### **Atmospheric Trace Molecule Spectroscopy Experiments**

The Atmospheric Trace Molecule Spectroscopy experiments investigated the chemistry and composition of the middle atmosphere using a modified interferometer. The interferometer obtained high-resolution infrared solar spectra every 2 seconds during orbital sunsets and sunrises, making use of the solar occultation technique in which the instrument looks through the atmosphere at the setting or rising sun. The availability of a bright source (i.e., the sun), a long atmospheric path length, the self-calibrating nature of the observation, and the high spectral and temporal resolution all combined to make the Atmospheric Trace Molecule Spectroscopy one of the most sensitive atmospheric chemistry instruments to ever fly in space.

The instrument was first flown on the Spacelab 3 (STS-51B) mission in April 1985 and then re-flown as part of the Atmospheric Laboratory for Applications and Science (ATLAS) series of payloads. The solar occultation nature of the observations provided limited latitude ranges for each mission, but the combination of shuttle orbit characteristics (e.g., launch time) and the occultation viewing geometry provided unique opportunities. For example, the flight in 1993 (STS-56) made sunrise observations at high Northern latitudes to best observe the atmospheric concentrations of “reservoir species” relevant to polar ozone depletion. The flight in 1994 (STS-66) provided the first opportunity to acquire comprehensive space-based atmospheric composition measurements on the state of large-scale, persistent polar cyclonic conditions. These allowed comparisons of photochemical conditions inside and outside the region of maximum ozone loss.

The results of these observations included several first detections of critical atmospheric species in addition to the 30 or more constituents for which profiles were derived at altitudes between 10 and 150 km (6 and 93 miles). These measurements, widely used to test the photochemical models of the stratosphere, have been important in addressing the vertical distribution of halogen- and nitrogen-containing molecules in the troposphere and stratosphere as well as in characterizing the isotopic composition of atmospheric water vapor. Atmospheric Trace Molecule Spectroscopy observations served as important validation information for instruments that flew aboard NASA’s Upper Atmosphere

Research Satellite on STS-48 (1991). Through its high-resolution infrared observations, the spectroscope also left an important legacy leading to observations aboard the Earth Observing System’s Aura satellite, launched in 2004. Aura’s instruments studied the atmosphere’s chemistry and dynamics and enabled scientists to investigate questions about ozone trends and air quality changes and their linkage to climate change.

The measurements also provided accurate data for predictive models and useful information for local and national agency decision support systems. Shuttle’s efforts provided the impetus for the Canadian Atmospheric Chemistry Experiment satellite, launched in 2003.

### **Aerosols in the Atmosphere—Tiny Particles, Big Influence**

Aerosols play an important role in our planet’s dynamic atmosphere and globally impacted our climate. For example, aerosols interact with clouds and influence their rain production, which could affect the health of oceanic life and coral reefs as they carry minerals. Scientists have documented that Africa’s Saharan dust particles (aerosols) travel all the way to South America to nourish the Amazonian rain forest. The Space Shuttle was well suited to facilitate research on these tiny particles that exert such a big influence on our atmosphere.

The vantage point of space has proven essential for understanding the global distribution of atmospheric aerosols, including horizontal and vertical distribution, chemical

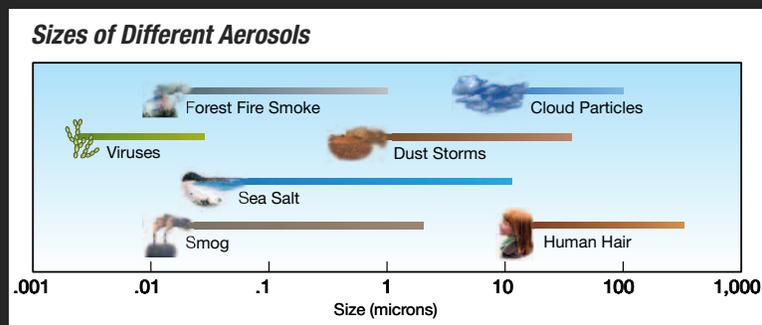


## Aerosols—A Mystery Revealed

Have you ever wondered why sunsets appear redder on some days? Or why the Earth becomes cooler after a volcanic eruption? The reason is aerosols.

Aerosols are minute particles suspended in the atmosphere (e.g., dust, sea salt, viruses, and smog). When these particles are sufficiently large, their presence is noticeable as they scatter and absorb sunlight. Their scattering of sunlight can reduce visibility (haze) and redden sunrises and sunsets. Aerosols affect our daily weather and have implications for transportation, among other impacts.

Aerosols interact both directly and indirectly with the Earth's climate. As a direct effect, aerosols scatter sunlight directly back into space. As an indirect effect, aerosols in the lower atmosphere can modify the size of cloud particles, changing how the clouds reflect and absorb sunlight, thereby affecting the Earth's energy budget and climatic patterns.



and optical properties, and interaction with the atmospheric environment. The diversity of aerosol characteristics makes it important to use a variety of remote sensing approaches. Satellite instruments have added dramatically to our body of knowledge. The Mediterranean Israeli Dust Experiment that flew on board

STS-107 in 2003 complemented these observations due to its viewing geometry (the inclined orbit of the shuttle provided data at a range of local times, unlike the other instruments in polar sun-synchronous orbits that only provided data at specific times of the day) and its range of wavelengths (from ultraviolet through visible into near-infrared).

### ***The Space Shuttle Columbia and Israeli Dust Experiment***

Space Shuttle Columbia's final flight carried the Mediterranean Israeli Dust Experiment by Tel Aviv University and the Israeli Space Agency.

The primary objective of this experiment was the investigation of desert aerosol physical properties and transportation, and its effect on the energy balance and chemistry of the ambient atmosphere with possible applications to weather prediction and climate change. The main region of interest for the experiment was the Mediterranean Sea and its immediate surroundings.

### ***How Do We Know the Distribution of Dust Particles?***

The experiment included instruments for remote as well as in-situ measurements of light scattering by desert aerosol particles in six light wavelengths starting from the ultraviolet region to the near-infrared. The supporting ground-based and airborne measurements included optical observations as well as direct sampling. Airborne measurements were conducted above dust storms under the shuttle orbit ground-track during the passage of the shuttle over the target area. The collocation and simultaneity of shuttle, aircraft, and ground-based correlated data were aimed to help validate the remote spaceborne observations from Columbia and other space platforms.

Since most data from this experiment were transmitted to the ground for

backup, the experiment's data were saved almost entirely and, after years of analysis, yielded a wealth of scientific data.

### ***Insights From the Mediterranean Dust Experiment***

Over 30% of the dust particles that pass over the Mediterranean Sea are coated with sulfate or sea salt. These particles play a crucial role in the development of clouds and precipitation as they often act as giant cloud condensation nuclei and enhance the development of rain. On January 28, 2003, a dust storm that interacted with a cold front, which produced heavy rain and flooding, was studied during this experiment. This is an example of how dust aerosols influence the local climate.

### ***Observing Transient Luminous Events***

In addition to measuring the dust particle distribution, the other major objective of the Israeli Dust Experiment was to use the same instruments at night to study electrical phenomena in the atmosphere. Scientists have known that large thunderstorms produce these electrical phenomena called “transient luminous events.”

These events occur in upper atmospheric regions of the stratosphere, mesosphere, or ionosphere. The most common events include Sprites and Elves. It is interesting to note that Elves were discovered in 1992 by video camera in the payload bay of the Space Shuttle.

## **Sprites and Elves— Phenomenal Flashes of Light**

So what are transient luminous events? They can best be defined as short-lived electrical phenomena generated as a result of enormous thunderstorms, and are categorized into Sprites and Elves.

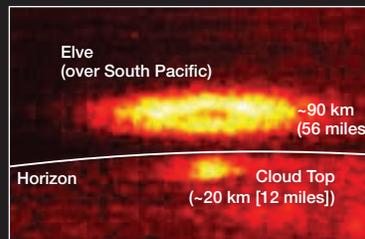
Sprites are jellyfish-shaped, red, large, weak flashes of light reaching up to 80 km (50 miles) above the cloud tops. They last only a few tens of microseconds. Seen at night, Sprites can be imaged by cameras and only rarely seen by human eyes.

Elves are disk-shaped regions of glowing light that can expand rapidly to large distances up to 483 km (300 miles) across. They last fewer than thousandths of a second. Space Shuttle low-light video cameras were the first to record the occurrence of Elves.

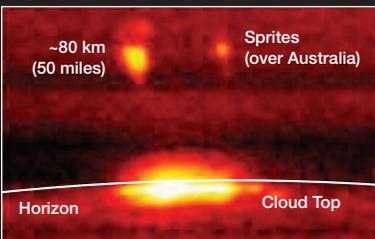
### ***Record-setting Measurements from Columbia (STS-107 [2003])***

The experiment succeeded in a spectacular fashion as almost all data on Sprites and Elves were saved, thereby yielding the first calibrated measurements of their spectral luminosity, first detection of Sprite emission in the near-infrared, and clear indication for the generation of Elves by intra-cloud lightning flashes. The global observations of transient luminous events enabled calculation of their global occurrence rate. These shuttle-based results are considered a benchmark for satellite observations.

#### ***Elves over the South Pacific***



#### ***Sprites over Southeast Australia***



*Short-lived electrical phenomena in upper atmosphere in disk-shaped regions (termed Elves) were imaged over the South Pacific. This was the first calibrated measurement of their spectral luminosity from space.*



## ***The Space Shuttle as an Engineering Test Bed***

### **The Lidar In-space Technology Experiment**

Scientists need the inventory of clouds and aerosols to understand how much energy is transmitted and lost in the atmosphere and how much escapes to space. To gain insight into these important questions, NASA explored the potential of lidar technology using the Space Shuttle as a test bed. Why lidar? Lidar's ability to locate and measure aerosols, water droplets, and ice particles in clouds gave scientists a useful tool for scientific insights.

### ***Why Use the Space Shuttle as a Test Bed for Earth-observing Payloads?***

The Space Shuttle could carry a large payload into low-Earth orbit, thereby allowing Earth-observing payloads an opportunity for orbital flight. Similarly, science goals might have required a suite of instruments to provide its measurements and, taken together, the instruments would have exceeded the possible spacecraft resources. Further, the shuttle provided a platform for showing a proof of concept when the technology was not mature enough for a long-duration, uncrewed mission. All of the above applied to the Lidar In-space Technology Experiment.

Laser technology was not at a point where the laser efficiencies and lifetime

requirements for a long-duration mission were feasible; however, the shuttle could fly the experiment with its over 1,800-kg (4,000-pound), 4-kilowatt requirements.

The Lidar In-space Technology Experiment, which was the primary payload on Space Transportation System (STS)-64 (1994), orbited the Earth for 11 days and ushered in a new era of remote sensing from space. It was the first time a laser-based remote sensing atmospheric experiment had been flown in low-Earth orbit.

### **How Did Lidar Work in Space?**

A spaceborne lidar can produce vertical profile measurements of clouds and aerosols in the Earth's atmosphere by accurately measuring the range and amount of laser light backscattered to the telescope. Using more than one laser color or wavelength produces information on the type of particle and/or cloud that is scattering the laser light from each altitude below.

The Lidar In-space Technology Experiment employed a three-wavelength laser transmitter. The lidar return signals were amplified, digitized, stored on tape on board the shuttle, and simultaneously telemetered to the ground for most of the mission using a high-speed data link.

The Lidar In-space Technology Experiment took data during ten 4½-hour data-taking sequences and five 15-minute "snapshots" over specific target sites. The experiment made measurements of desert dust layers, biomass burning, pollution outflow off continents, stratospheric

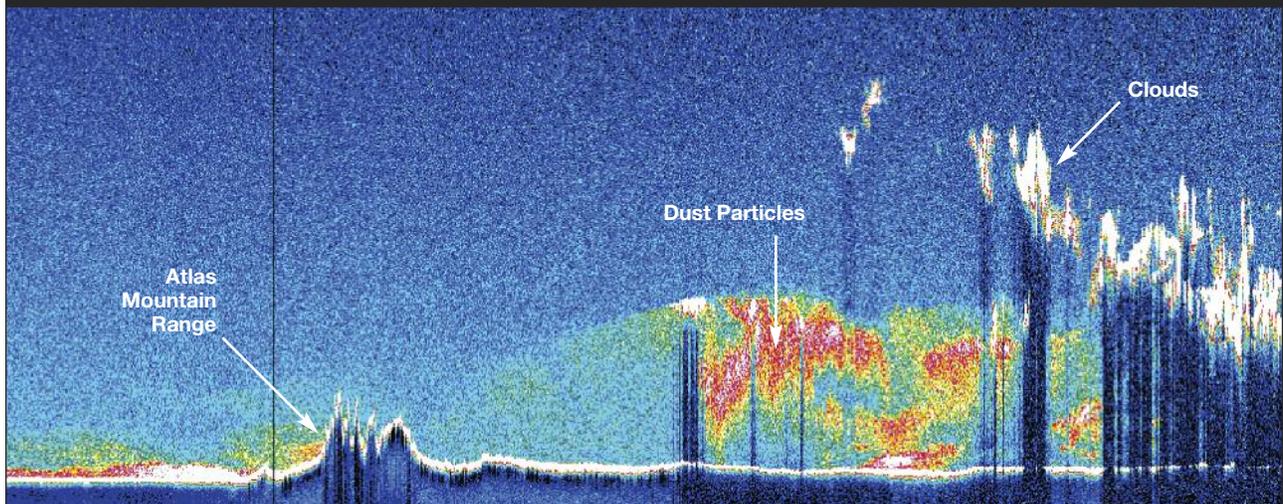
## **Of Lasers and Lidar: What is Laser? What is Lidar?**

You have heard about use of lasers in eye surgery or laser printer for your computer or laser bar code readers in stores. So, what is a laser? Laser is short for Light Amplification by Stimulated Emission of Radiation. Unlike ordinary light composed of different wavelengths, laser light is one wavelength. All of its energy is focused in one narrow beam that can produce a small point of intense energy. Lasers are used in "radar-like" applications and are known as Lidars.

What is a lidar? It stands for Light Detection and Ranging and is an optical technology that uses pulsed lasers. It measures properties of scattered light to find range and/or other information of a distant target. As with similar radar technology, which uses radio waves, with a lidar the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. Lidar technology has application in many Earth Science disciplines.



### Lidar Maps Saharan Dust Transport

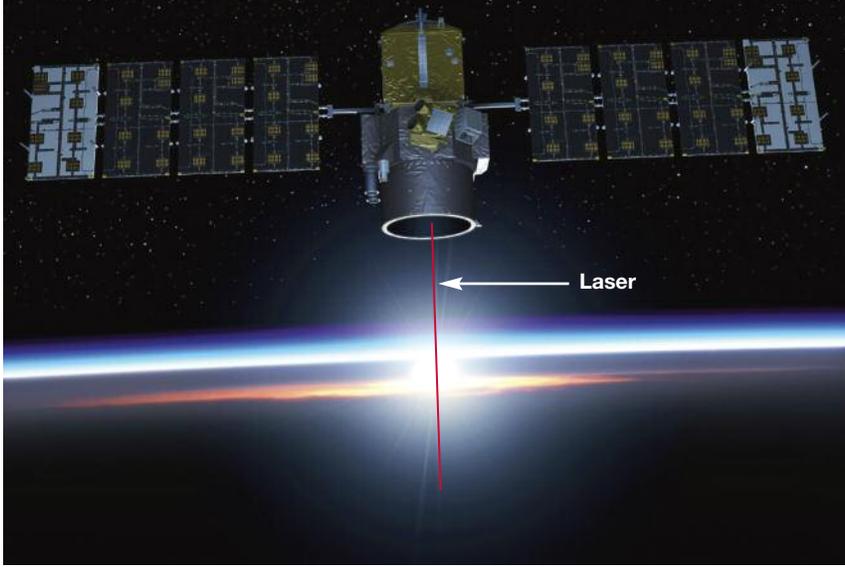


Lidar data during STS-64 (1994) depict widespread transport of dust aerosols over the African Sahara. The Atlas Mountain range appears to separate a more optically thick aerosol air mass to the Southeast from a relatively cleaner air mass to the Northwest. Over the desert interior, the aerosol plume extends in altitude to about 5 km (3 miles) with complex aerosol structures embedded within the mixed layer.

volcanic aerosols, and storm systems. It observed complex cloud structures over the intertropical convergence zone, with lasers penetrating the uppermost layer to four and five layers below.

Six aircraft, carrying a number of up- and down-looking lidars, performed validation measurements by flying along the shuttle footprint. NASA also coordinated ground-based lidar and other validation measurements—e.g., balloon-borne dustsondes—with the experiment’s overflights. Photography took place from the shuttle during daylight portions of the orbits. A camera, fixed and bore sighted to the Lidar In-space Technology Experiment, took pictures as did the astronauts using two Hasselblad cameras and one camcorder to support the experiment’s measurements.

### Space Shuttle Legacy of Lidar In-space Technology Experiment



The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations satellite was launched in 2006 on a delta rocket to provide new information about the effects of clouds and aerosols on changes in the Earth’s climate. The major instrument is a three-channel lidar.



### ***Lidars in Space—A New Tool for Earth Observations***

The Lidar In-space Technology Experiment mission proved exceedingly successful. It worked flawlessly during its 11-day mission. Data were used to show the efficacy of measuring multiple-layered cloud systems, desert dust, volcanic aerosols, pollution episodes, gravity waves, hurricane characterization, forest fires, agricultural burning, and retrieving winds near the ocean's surface. All measurements were done near-globally with a vertical resolution of 15 m (49 ft), which was unheard of using previous remote sensors from space. The Lidar In-space Technology Experiment even showed its utility in measuring land and water surface reflectivity as well as surface topography.

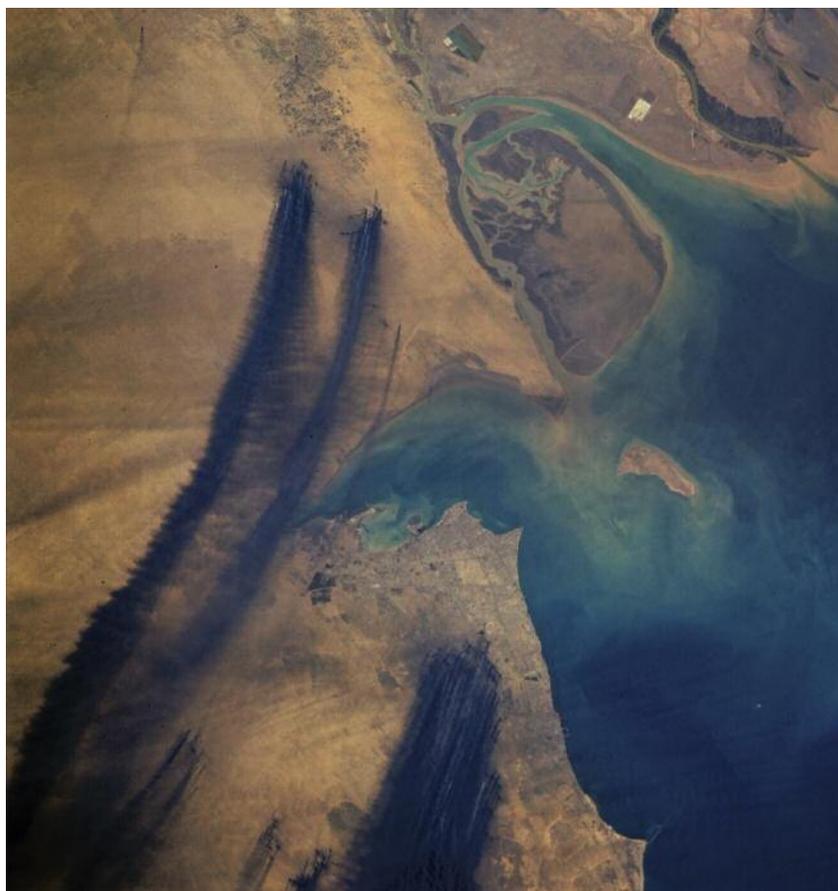
- It showed that space lidars could penetrate to altitudes of within 2 km (1.2 miles) of the surface 80% of the time and reach the surface 60% of the time, regardless of cloud cover. It appeared that clouds with optical depths as high as 5 to 10 km (3 to 6 miles) could be studied with lidars. The comparison of shuttle lidar data and lidar data acquired on board the aircraft was remarkable, with each showing nearly identical cloud layering and lower tropospheric aerosol distributions.
- The mission introduced a new technology capable of a global data set critical for understanding many atmospheric phenomena, such as global warming and predicting future climates.

- It provided a benefit in developing long-duration lidars for uncrewed satellite missions. Simulations using the experiment's characteristics and data have been carried out by groups all over the world in developing the feasibility of various lidar concepts for space application. This effort manifested itself, for example, in the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations experiment—a joint US/French mission flying a lidar as its centerpiece experiment.

### ***A National Treasure—Space Shuttle-based Earth Imagery***

Have you ever imagined gazing through the Space Shuttle windows at our own magnificent planet? Have you wondered what an ultimate field trip experience that could be?

Space Shuttle astronauts have experienced this and captured their observations using a wide variety of cameras. To these astronauts, each



*This image of Kuwait and the Persian Gulf was taken from STS-37 (1991) after oil wells were set on fire by Iraqi forces in February 1991. Black smoke plumes are prominently seen. Kuwait City is located on the south side of Kuwait Bay.*



## Shuttle Imagery Captures Earth's Dynamic Processes



Astronauts photographed many sites of ecological importance from their missions over the 30 years of the Space Shuttle Program. These images yielded unprecedented insights into the changes occurring on Earth's surface.

One such site repeatedly imaged by shuttle crews was Lake Chad. This vast, shallow, freshwater lake in Central Africa straddles the borders of Chad, Niger, Nigeria, and

Cameroon. Once the size of Lake Erie in the United States some 40 years ago, the shrinking of this lake was recorded on shuttle Earth imagery. First photographed by Apollo 7 astronauts in 1968—when the lake was at its peak—the decline in water levels is clearly seen from a small sampling of time series from shuttle flights in 1982, 1992, and 2000. While estimates of decline vary due to seasonal fluctuations,

experts confirm that less than 25% of the water remains in the southern basin.

What has caused the shrinking of this life-supporting source of water for millions of people in Central Africa? Researchers point to a combination of factors—natural climatic changes ushering in drier climate, deforestation, aquatic weed proliferation, overgrazing in the region, and water use for agriculture and other irrigation projects.

*\*Images not rectified to scale*

shuttle mission offered a window to planet Earth in addition to whatever else the mission involved.

Astronauts have used handheld cameras to photograph the Earth since the dawn of human spaceflight programs. Beginning with the Mercury missions in the early 1960s, astronauts have taken more than 800,000 photographs of Earth. During the Space Shuttle Program, astronauts captured over 400,000 images using handheld cameras alone.

### ***Making Astronauts “Earth Smart”***

Shuttle astronauts were trained in scientific observation of geological, oceanographic, environmental, and meteorological phenomena as well as in the use of photographic equipment and techniques. Scientists on the ground selected and periodically updated a series of areas to be photographed as part of the crew Earth observations. Flight notes were routinely sent to the shuttle crew members, listing the best opportunities for photographing

target site areas. The sites included major deltas in South and East Asia, coral reefs, major cities, smog over industrial regions, areas that typically experience floods or droughts triggered by El Niño cycles, alpine glaciers, long-term ecological research sites, tectonic structures, and features on Earth—such as impact craters—that are analogous to structures on Mars.



### ***Scientific and Educational Uses of Astronaut Earth Imagery***

Shuttle Earth imagery filled a niche between aerial photography and imagery from satellite sensors and complemented these two formats with additional information. Near real-time information exchange between the crew and scientists expedited the recording of dynamic events of scientific importance.

Critical environmental monitoring sites are photographed repeatedly

over time; some have photographic records dating back to the Gemini and Skylab missions. Images are used to develop change-detection maps. Earth limb pictures taken at sunrise and sunset document changes in the Earth's atmospheric layering and record such phenomena as auroras and noctilucent clouds. Shuttle photographs of hurricanes, thunderstorms, squall lines, island cloud wakes, and the jet stream supplement satellite images. Other observations of Earth made by flight crews are used not only as scientific

data but also to educate students and the general public about the Earth's ever-changing and dynamic systems. Over 3,000,000 images are downloaded, globally, each month by the public (<http://eol.jsc.nasa.gov/>). Educators, museums, science centers, and universities routinely use the imagery in their educational pursuits.

This imagery, archived at NASA, is a national treasure that captures the unique views of our own habitat acquired by human observers on orbit.



*A mighty volcanic eruption of Mount St. Helens in 1980 and a large earthquake altered the landscape of this serene region in a blink of an eye. Landslides and rivers of rocks rushed downhill, causing havoc. Volcanic ash traveled more than 322 km (200 miles). This shuttle image from STS-64 (1994) captures the impact of these dynamic events in the US Pacific Northwest.*



**Jack Kaye, PhD**

Associate director for research at NASA Headquarters Earth Science Division.

**The Role of the Space Shuttle in Earth System Science**



*“The Space Shuttle played a significant role in the advancement of Earth System Science. It launched major satellites that helped revolutionize our study of the Earth. Its on-board experiments provided discoveries and new climatologies never before available, such as the tropospheric carbon monoxide distributions measured by the Measurement of Air Pollution from Satellite experiment, the stratospheric vertical profiles of many halogen-containing species important in ozone depletion measured by the Atmospheric Trace Molecule Spectroscopy instrument, and the high-resolution surface topography measurements made by the Shuttle Radar Topography Mission. It provided for multiple flight opportunities for highly calibrated instruments used to help verify results from operational and research satellites, most notably the eight flights of the Shuttle Solar Backscatter Ultraviolet instrument. Shuttle flights provided for on-orbit demonstration of techniques that helped pave the way for subsequent instruments and satellites. For example, the Lidar In-space Technology Experiment, with its*

*demonstration of space-based lidar to study aerosols and clouds, paved the way for the US-French Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation satellite. Similarly, the Shuttle Ozone Limb Sounding Experiment and Limb Ozone Retrieval Experiment provided demonstrations of the experimental technique to be used by the Ozone Mapping and Profiling Suite’s limb sensor aboard the National Polar-orbiting Operational Environmental Satellite System Preparatory Project. The shuttle enabled international cooperation, including the multinational Atmospheric Laboratory for Applications and Science payload that included instruments with principal investigators from Germany, France, and Belgium among its six instruments, as well as deployment of the German Cryogenic Infrared Spectrometers & Telescopes for the Atmosphere-Shuttle Palette Satellite. The shuttle provided launch capability for Earth Science-related experiments to the International Space Station, such as the launch of the French Solar Spectrum Measurement instrument. Finally, the shuttle provided outstanding education and outreach opportunities.”*

**Summary**

The Space Shuttle played a significant role in NASA’s missions to study, understand, and monitor Earth system processes. The shuttle was an integral

component of the agency’s missions for understanding and protecting our home planet. In the end, Space Shuttle missions for Earth observations were not only about science or instruments or images—these missions were also about humanity’s journey

into space to get a glimpse of our planet from a new perspective and rediscover our own home.



## Mapping the Earth: Radars and Topography

Michael Kobrick  
Kamlesh Lulla

*One of the Space Shuttle's enduring science legacies is the near-global topographic mapping of the Earth with innovative radar remote sensing technologies. The shuttle also served as an important engineering test bed for developing the radar-based mapping technologies that have ushered in a quiet revolution in mapping sciences. The Shuttle Radar Topography Mission data set, in particular, has had an enormous impact on countless scientific endeavors and continues to find new applications that impact lives. This mission helped create the first-ever global high-resolution data for Earth topography—a data set for the ages. On average, one Shuttle Radar Topography Mission-derived topographic data set is downloaded from the US Geological Survey's servers every second of every day—a truly impressive record. Experts believe the mission achieved what conventional human mapmaking was unable to accomplish—the ability to generate uniform resolution, uniform accuracy elevation information for most of the Earth's surface.*

*In all, the development of imaging radars using the shuttle demonstrated, in dramatic fashion, the synergy possible between human and robotic space operations. Radar remote sensing technology advanced by leaps and bounds, thanks to the five shuttle flights, while producing spectacular science results.*

## “Seeing” Through the Clouds

### *What Is Imaging Radar?*

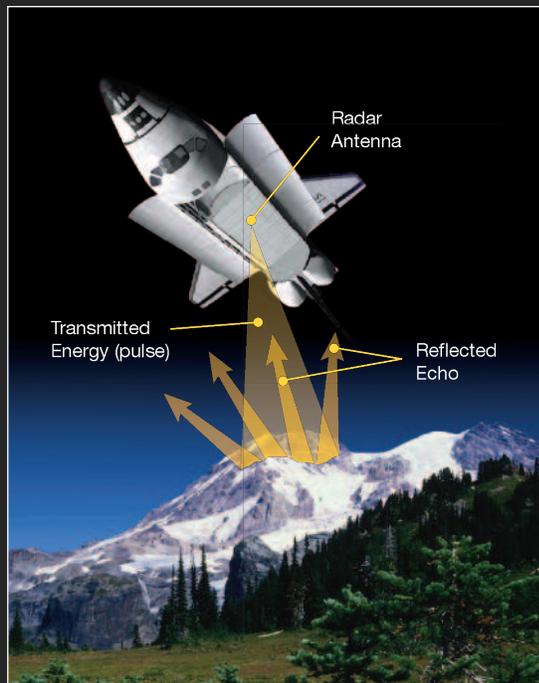
The term radar stands for Radio Detection and Ranging. You have seen radar images of weather patterns on television.

Typical radar works like a flash camera, so it can operate day or night. But, instead of a lens and a film, radar uses an antenna to send out energy (“illumination”) and computer tapes to record the reflected

“echoes” of pulses of “light” that comprise its image. Radar wavelengths are much longer than those of visible light so it can “see” through clouds, dust, haze, etc. Radar antenna alternately transmits and receives pulses at a particular microwave wavelength (range of 1 cm [0.4 in.] to several meters [feet]). Typical imaging radar systems transmit around 1,500 high-power pulses per second toward the area or surface to be imaged.

### *What Is Synthetic Aperture Radar?*

When a radar is moving along a track, it is possible to combine the echoes received at various positions to create a sort of “radar hologram” that can be further processed into an image. The improved resolution that results would normally require a much larger antenna, or aperture, thus a “synthetic aperture” is created.



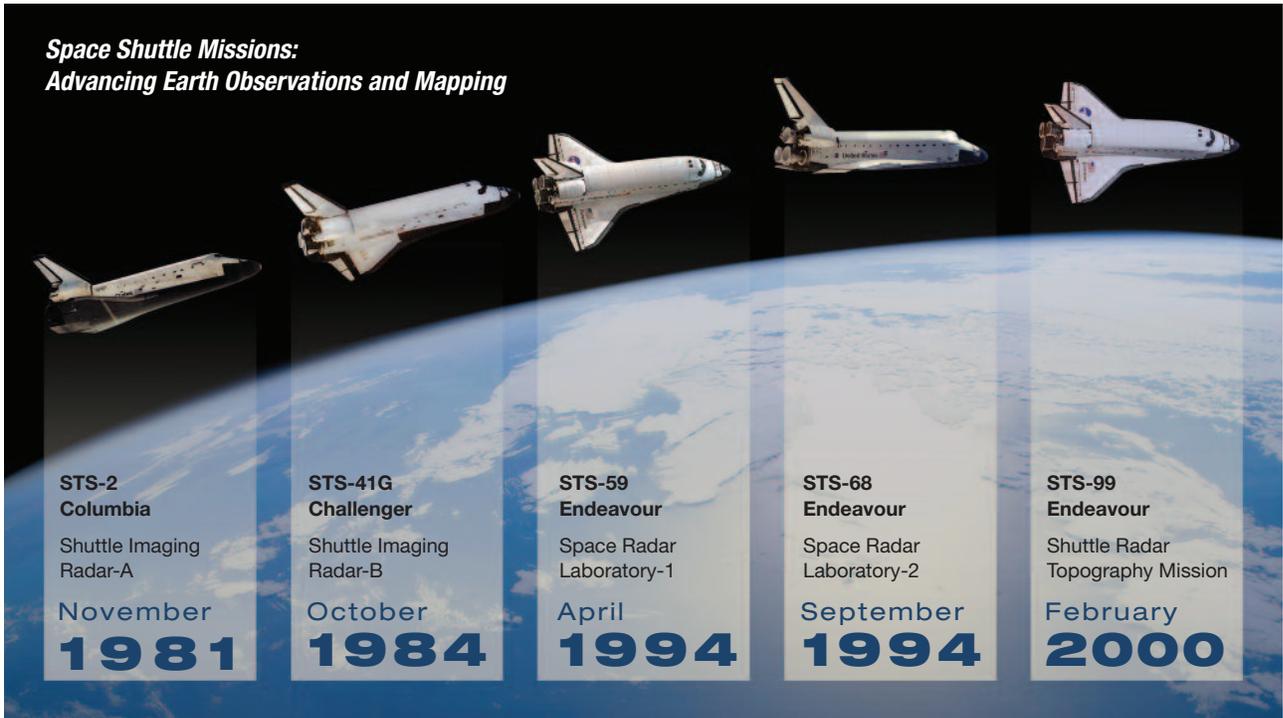
*How does radar work? A radar transmits a pulse, then measures the reflected echo.*

## Why Do We Need Accurate Topographic Maps of the Earth?

If you have ever used a global positioning system for navigation, you know the value of accurate maps. But, have you ever wondered how accurate the height of Mount Everest is on a map or how its height was determined? One of the foundations of many science disciplines and their applications to societal issues is accurate knowledge of the Earth’s surface, including its topography. Accurate elevation maps have numerous common and easily understood civil and military applications, like locating sites for communications towers and ground collision avoidance systems for aircraft. They are also helpful in planning for floods, volcanic eruptions, and other natural disasters, and even predicting the viewscape for a planned scenic highway or trail.

It is hard to imagine that the global topographic data sets through the end of the 20th century were quite limited. Many countries created and maintained national mapping databases, but these databases varied in quality, resolution, and accuracy. Most did not even use a common elevation reference so they could not be easily combined into a more global map. Space Shuttle radar missions significantly advanced the science of Earth mapping.

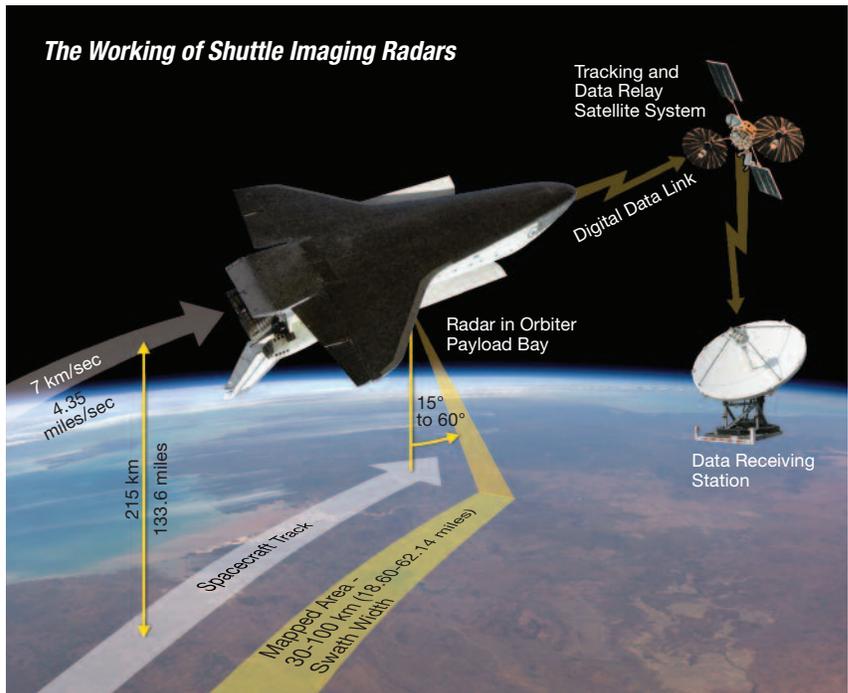
**Space Shuttle Missions:  
Advancing Earth Observations and Mapping**



**Shuttle and Imaging Radars—A Quiet Revolution in Earth Mapping**

**The First Mission**

The Shuttle Imaging Radar-A flew on Space Shuttle Columbia (Space Transportation System [STS]-2) in November 1981. This radar was comprised of a single-frequency, single-polarization (L-band wavelength, approximately 24-cm [9-in.]) system with an antenna capable of acquiring imagery at a fixed angle and a data recorder that used optical film. Shuttle Imaging Radar-A worked perfectly, and the radar acquired images covering approximately 10 million km<sup>2</sup> (4 million miles<sup>2</sup>) from regions with surface covers ranging from tropical



Space Shuttle's track at the altitude of 215 km (134 miles) with changing radar antenna look angle allowed the mapping of swaths up to 100 km (62 miles) wide.

forests in the Amazon and Indonesia to the completely arid deserts of North Africa and Saudi Arabia. Analysts found the data to be particularly useful in geologic structure mapping, revealing features like lineaments, faults, fractures, domes, layered rocks, and outcrops. There were even land-use applications since radar is sensitive to changes in small-scale roughness, surface vegetation, and human-made structures. Urban regions backscatter strongly, either because the walls of buildings form corner reflectors with the surface or because of the abundance of metallic structures—or both.

The Shuttle Imaging Radar-A's most important discovery, however, resulted from a malfunction. STS-2 was planned as a 5-day excursion and the payload operators generated an imaging schedule to optimize use of the radar's 8-hour supply of film. But early on, one of the three Orbiter fuel cells failed, which by mission rules dictated a minimum-duration flight—in this case, a bit over 2 days. So, the operators quickly retooled the plan to use the film in that time frame and ended up running the system whenever the Orbiter was over land. The result was a number of additional unplanned image passes over Northern Africa, including the hyper-arid regions of the Eastern Sahara.

### ***“Radar Rivers” Uncovered***

This Sahara region, particularly the Selima Sand Sheet straddling the Egypt/Sudan border, is one of the driest places on our planet. Photographs from orbit show nothing but vast, featureless expanses of sand, and with good reason. The area gets rain no more than two or three times per century, and rates a 200 on the geological aridity index.



**Left:** Optical view of the Sahara region (Africa) showing the vast, featureless expanse of sand. The white lines depict the radar flight path.

**Right:** Radar imagery over the same region, taken during STS-2 (1981), reveals the network of channels and dried-up rivers (radar rivers) beneath the sand sheets, thereby illustrating the power of radar for archeological mapping.

For comparison, California's Death Valley—the driest place in the United States—rates no more than a 7 on the geological aridity index.

But when scientists got their first look at the Shuttle Imaging Radar-A images, they said “Hey, where's the sand sheet?” Instead of the expected dark, featureless plain, they saw what looked like a network of rivers and channels that covered virtually all the imaged area and might extend for thousands of kilometers (miles). To everyone's surprise, the radar waves had penetrated 5 or more meters (16 or more feet) of loose, porous sand to reveal the denser rock, gravel, and alluvium marking riverbeds that had dried up and been covered over tens of thousands of years ago.

Scientists knew the Sahara had not always been dry because some 50 million years ago, large mammals roamed its lush savannahs, swamps, and grasslands. Since then, the region has fluctuated between wet and dry, with periods during which rivers carved a complex drainage pattern

across the entire Northern part of the continent. The existence of wadis (dry valleys) carved in Egypt's nearby Gilf Kebir Plateau, as well as other geologic evidence, supports this idea.

Subsequent field expeditions and excavations verified the existence of what came to be called the “radar rivers” and even found evidence of human habitation in the somewhat wetter Neolithic period, about 10,000 years ago. This discovery of an evolving environment was a harbinger of current concerns about global climate change, evoking historian Will Durant's statement, “Civilization exists by geological consent, subject to change without notice.”

### **The Second Mission**

The Shuttle Imaging Radar-B mission launched October 5, 1984, aboard the Space Shuttle Challenger (STS-41G) for an 8-day mission. This radar, again L-band, was a significant improvement, allowing multi-angle imaging—a capability achieved by

using an antenna that could be mechanically tilted. It was also designed as a digital system, recording echo data to a tape recorder on the flight deck for subsequent downlink to the ground but with Shuttle Imaging Radar-A's optical recorder included as a backup. The results, deemed successful, included the cartography and stereo mapping effort that produced early digital-elevation data.

### Next Generation of Space Radar Laboratory Missions

The Shuttle Imaging Radar instrument expanded to include both L-band (24 cm [9 in.]) and C-band (6 cm [2 in.]) and, with the inclusion of the German/Italian X-band (3 cm [1 in.]), radar. For the first time, an orbiting radar system not only included three wavelengths, the instrument was also fully polarimetric, capable of acquiring data at both horizontal and vertical polarizations or anything in between. It also used the first "phased-array" antenna, which meant it could be electronically steered to point at any spot on the ground without any motion of the antenna or platform. The resulting multiparameter images could be combined and enhanced to produce some of the most spectacular and information-rich radar images ever seen.

The Space Radar Laboratory missions (1 and 2) in 1994 were an international collaboration among NASA, the Jet Propulsion Laboratory, the German Space Agency, and the Italian Space Agency and constituted a real quantum leap in radar design, capability, and performance.

**Tom Jones, PhD**  
Astronaut on  
STS-59 (1994),  
STS-68 (1994),  
STS-80 (1996), and  
STS-98 (2001).



*"Space Radar Laboratory-1 and -2 orbited*

*a state-of-the-art multifrequency radar observatory to examine the changing state of Earth's surface. Our STS-59 and STS-68 crews were integral members of the science team. Both missions returned, in total, more than 100 terabytes of digital imagery and about 25,000 frames of detailed Earth photography targeted on more than 400 science sites around the globe.*

*"For our crews, the missions provided a glorious view of Earth from a low-altitude, high-inclination orbit. Earth spun slowly by our flight deck windows, and we took advantage of the panorama with our 14 still and TV cameras. On September 30, 1994, on Space Radar Laboratory-2, we were treated to the awesome sight of Kliuchevskoi volcano in full eruption, sending a jet-like plume of ash and steam 18,288 m (60,000 ft) over Kamchatka. Raging wildfires in Australia, calving glaciers in Patagonia, plankton blooms in the Caribbean, and biomass burning in Brazil showed us yet other faces of our dynamic Earth. These two missions integrated our crews into the science team as orbital observers, providing 'ground truth' from our superb vantage point. Flight plan duties notwithstanding, I found it hard to tear myself away from the windows and that breathtaking view.*

*"Both missions set records for numbers of individual Orbiter maneuvers (~470 each) to point the radars, and required careful management of power resources and space-to-ground payload communications. The demonstration of precise orbit adjustment burns, enabling repeat-pass interferometry with the radar, led to successful global terrain mapping by the Shuttle Radar Topography Mission (STS-99) in 2000."*

## The Shuttle Radar Topography Mission— A Quantum Leap in Earth Mapping

The Shuttle Radar Topography Mission was major a breakthrough in the science of Earth mapping and remote sensing—a unique event. NASA, the Jet Propulsion Laboratory, the National Geospatial-Intelligence Agency (formerly the Defense Mapping Agency Department of Defense), and the German and Italian Space Agencies all collaborated to accomplish the goals of this mission. The 11-day flight of the Space Shuttle Endeavour for the Shuttle Radar Topography Mission acquired a high-resolution topographic map of the Earth’s landmass (between 60°N and 56°S) and tested new technologies for deployment of large, rigid structures and measurement of their distortions to extremely high precision.

### How Did the Shuttle Radar Topography Mission Work?

The heart of this mission was the deployable mast—a real engineering marvel. At launch, it was folded up inside a canister about 3 m (10 ft) long. The mast had 76 bays made of plastic struts reinforced with carbon fiber, with stainless-steel joints at the corners and titanium wires held taut by 227 kg (500 pounds) of tension. The strict requirements of interferometry dictated that the mast be incredibly rigid and not flex by more than a few centimeters (inches) in response to the firing of the Orbiter’s attitude control vernier jets. It didn’t. Once in orbit, a helical screw

## Generating Three-dimensional Images

**The Interferometry Principle**

Radar wavefronts combine to form interference pattern.

Interference pattern is distorted by topography.

Residual fringes are topographic contours used to generate digital elevation map.

Processing detects and removes fringe distortions.

The diagram illustrates the process of generating a 3D topographic map. It starts with a shuttle in orbit emitting radar wavefronts that hit the Earth's surface. These wavefronts create an interference pattern that is distorted by the terrain's topography. This distorted pattern is then processed to detect and remove fringe distortions, resulting in residual fringes which are topographic contours. These contours are used to generate a digital elevation map (DEM).

### What Is Radar Interferometry?

When two sets of radar signals are combined, they create interference patterns. The measurement of this interference is called interferometry.

For example, if someone imagines a person standing with both arms extended to his or her sides and that person is holding a pebble (representing one radar each) in each hand but then drops the pebbles into a pond, two rippling concentric circles (representing radar signals) would emanate from the splash. As the two waves travel outward, they will eventually combine with each other causing “interference” patterns.

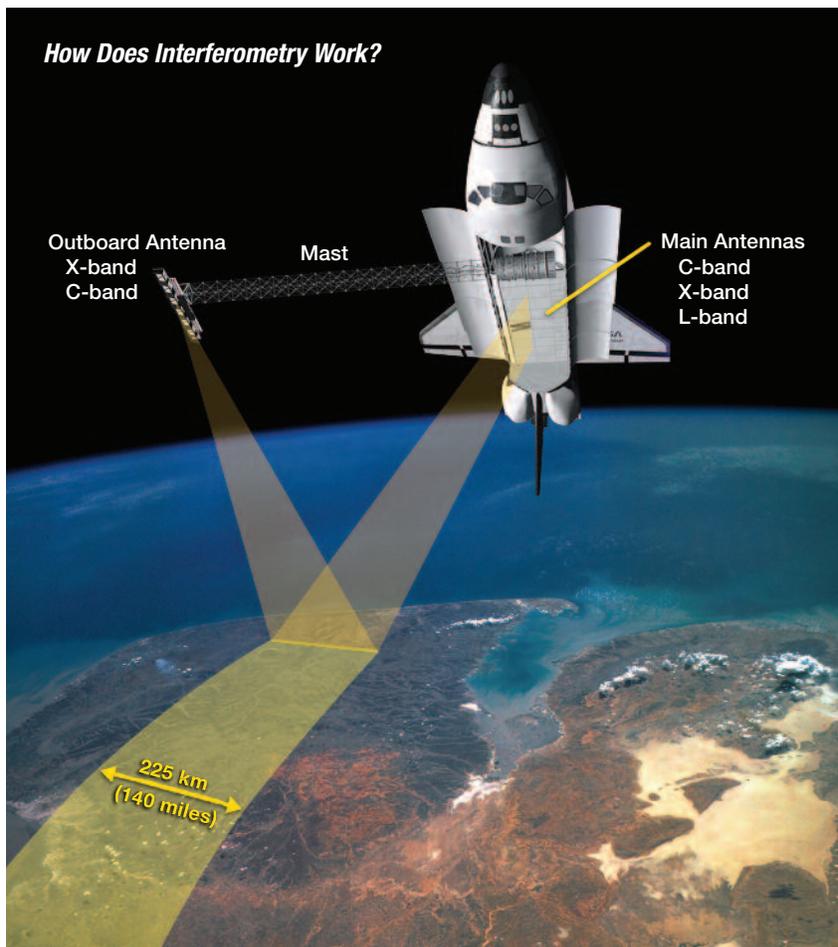
Similar patterns are generated when signals from two radar antennas are combined. Elevation differences on the surface cause distortions in the fringes that can be measured to determine the elevations. This was the concept used in the Shuttle Radar Topographic Mapping mission.

mechanism pulled the mast open and unfurled it one “bay” at a time to the mast’s full length of 60 m (197 ft).

A crucial aspect of the mapping technique was determination of the interferometric baseline. The Shuttle Radar Topography Mission was designed to produce elevations such

that 90% of the measured points had absolute errors smaller than 16 m (52 ft), consistent with National Mapping Accuracy Standards, and to do so without using ground truth—information collected “on location.” Almost all conventional mapping techniques fit the results to ground truth, consisting of arrays of points

### How Does Interferometry Work?



*This interferometry concept was used in the Shuttle Radar Topography Mapping mission. Radars on the mast (not to scale) and in the shuttle payload bay were used to map a swath of 225 km (140 miles), thus covering over 80% of the Earth's landmass.*

with known locations and elevations, to remove any residual inaccuracies. But, because the Shuttle Radar Topography Mission would be mapping large regions with no such known points, the system had to be designed to achieve that accuracy using only internal measurements.

This was a major challenge since analysis showed that a mere 1-arc-second error in our knowledge of the absolute orientation of the mast

would result in a 1-m (3-ft) error in the elevation measurements. A 1-arc-second angle over the 60-m (197-ft) baseline is only 0.3 mm (0.1 in.)—less than the thickness of a penny.

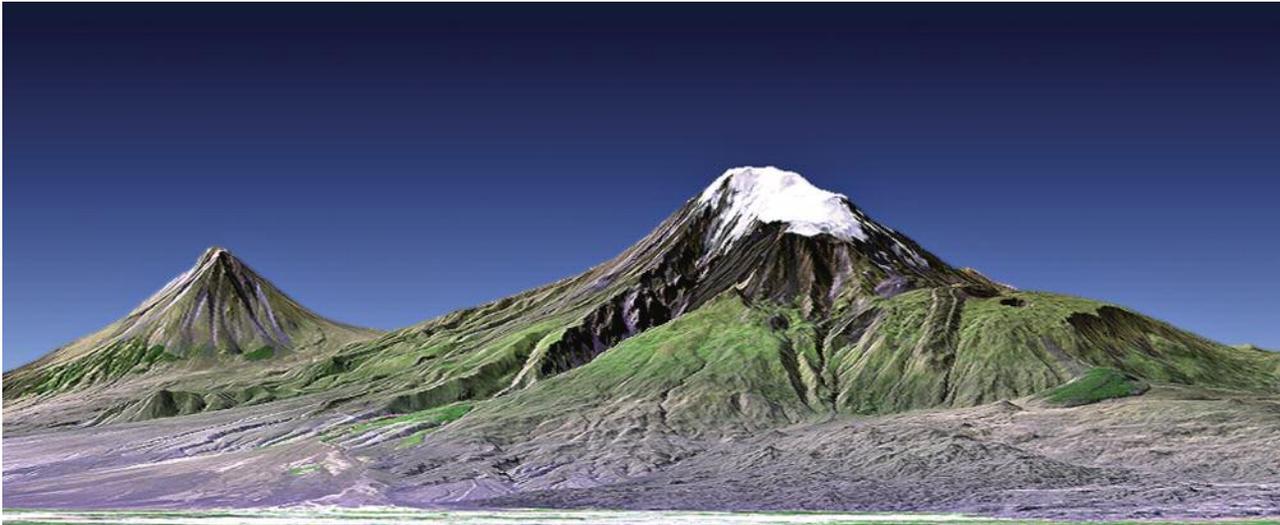
This problem was solved by determining the Orbiter's attitude with an inertial reference unit borrowed from another astronomy payload, augmented with a new star tracker. To measure any possible bending of the mast, the borrowed star tracker was

mounted on the main antenna to stare at a small array of light-emitting diodes mounted on the other antenna at the end of the mast. By tracking the diodes as if they were stars, all mast flexures could be measured and their effects removed during the data processing.

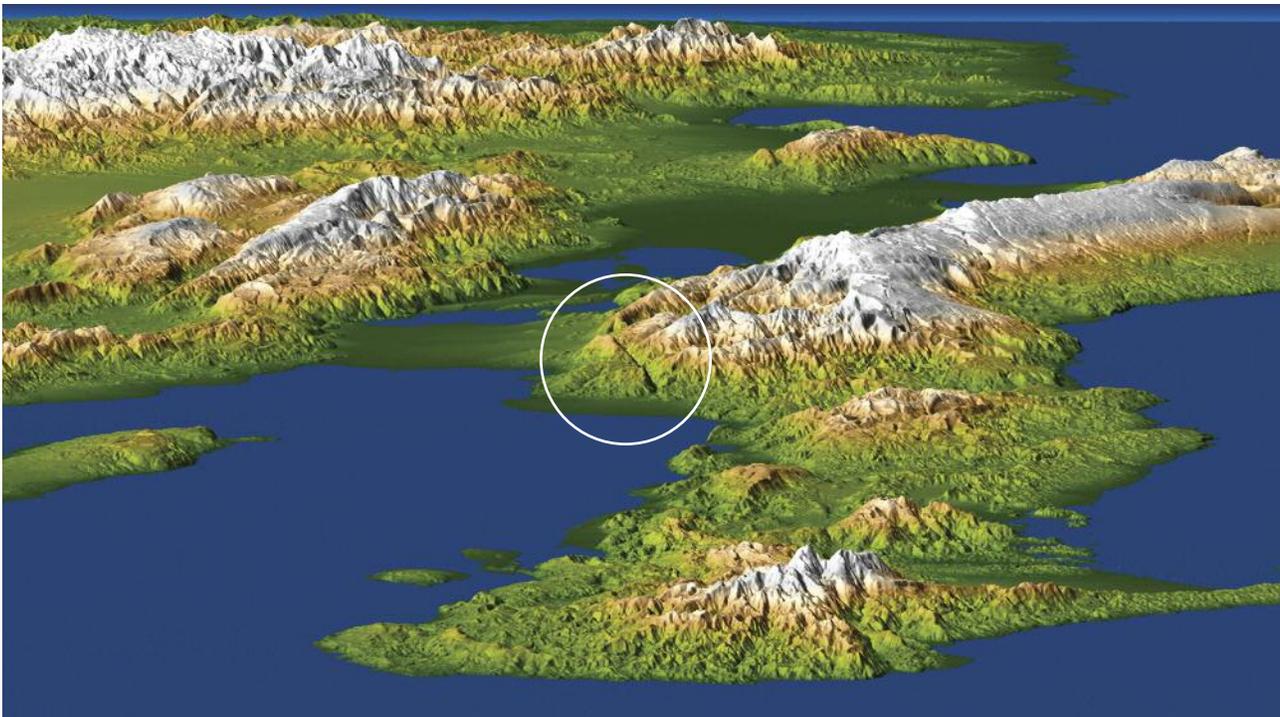
The mast-Orbiter combination measured 72 m (236 ft) from wingtip to the end of the mast, making it the largest solid object ever flown in space at that time. This size created one interesting problem: The Orbiter had to perform a small orbit maintenance burn using the Reaction Control System about once per day to maintain the proper altitude, and analysis showed that the resulting impulse would generate oscillations in the mast that would take hours to die out and be too large for the Shuttle Radar Topography Mission to operate.

By collaborating, Johnson Space Center flight controllers and Jet Propulsion Laboratory mechanical engineers arrived at a firing sequence involving a series of pulses that promised to stop the mast dead at the end of the burn. They called it the “flycast maneuver” since it mimicked the way a fisherman controls a fly rod while casting. The maneuver involved some tricky flying by the pilots and required much practice in the simulators, but it worked as planned. It also gave the crew an excuse to wear fishing gear in orbit—complete with hats adorned with lures—and produced some amusing photos.

NASA developed the original flight plan to maximize the map accuracy by imaging the entire landscape at least twice while operating on both ascending and descending orbits,



*Turkey: Mount Ararat was mapped with a Shuttle Radar Topographic Mapping elevation model and draped with a color satellite image. This view has been vertically exaggerated 1.25 times to enhance topographic expression. This peak is a well-known site for searches for the remains of Noah's Ark. The tallest peak rises to 5,165 m (16,945 ft).*



*Haiti: This pre-earthquake image clearly shows the Enriquillo fault that probably was responsible for the 7.0-magnitude earthquake on January 12, 2010. The fault is visible as a prominent linear landform that forms a sharp diagonal line at the center of the image. The city of Port-au-Prince is immediately to the left (North) at the mountain front and shoreline.*

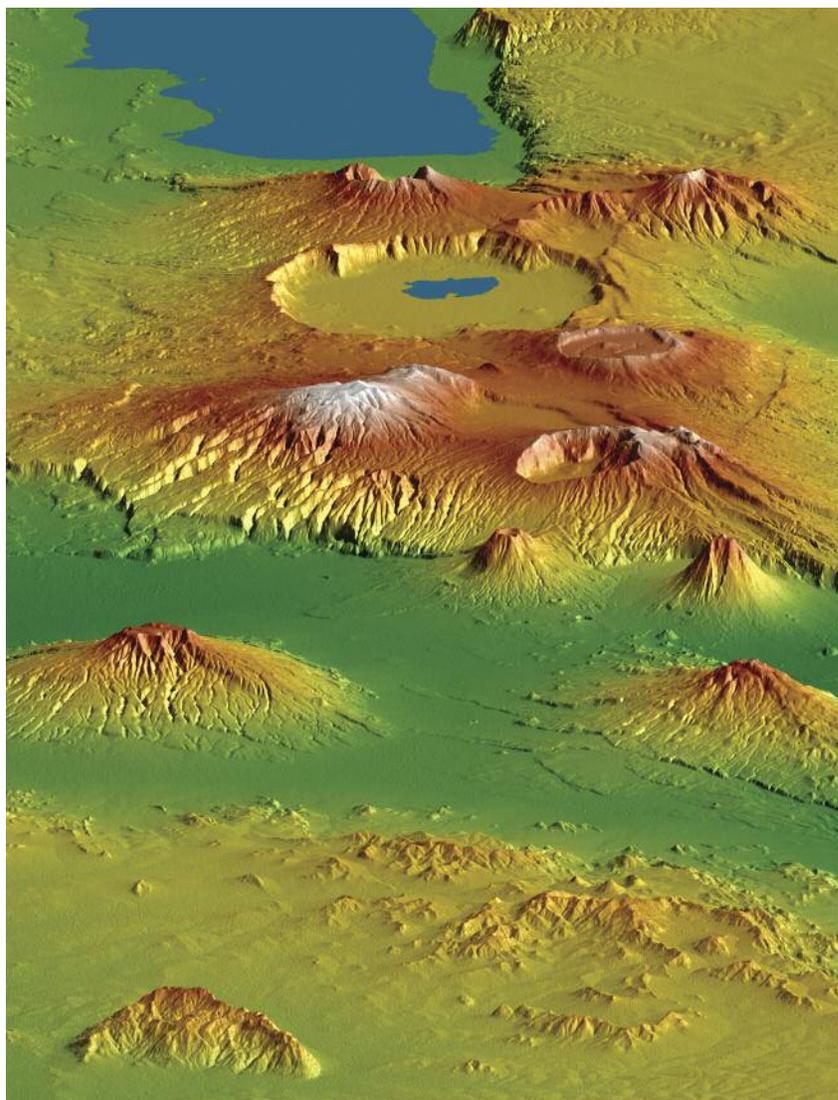
but it turned out that a limited region was covered only once because the mapping had to be terminated a few orbits early when the propellant ran low. This had a minor impact, however, because even a single image could meet the accuracy specifications. In addition, the affected regions were mostly within the already well-mapped US terrain near the northern and southern limits of the orbits where the swaths converged were covered as much as 15 to 20 times. In all, the instrument covered 99.96% of the targeted landmass.

### Converting Data Sets Into Real Topographic Maps

NASA assembled a highly effective computerized production system to produce topographic maps for users. Successful completion of radar data collection from Endeavour's flight was a major step, but it was only the first step. Teams from several technical areas of microwave imaging, orbital mechanics, signal processing, computer image processing, and networking worked together to generate the products that could be used by the public and other end users. Major steps included: rectifying the radar data to map coordinates, generating mosaics for each continent, performing quality checks at each stage, and assessing accuracy.

### Results of Shuttle Radar Topography Mission

The mission collected 12 terabytes of raw data—about the same volume of information contained in the US Library of Congress.



*Africa: Tanzania's Crater Highlands along the East African Rift Valley are depicted here as mapped with the Shuttle Radar Topographic Mapping elevation model with vertical exaggeration of two times to enhance topographic variations. Lake Eyasi (top of the image, in blue) and a smaller crater lake are easily seen in this volcanic region. Mount Loolmalasin (center) is 3,648 m (11,968 ft).*

Processing those data into digital elevation maps took several years, even while using the latest supercomputers. Yet, the Shuttle Radar Topography Mission eventually produced almost 15,000 data files, each covering 1° by 1° of latitude

and longitude and covering Earth's entire landmass from the tip of South America to the southern tip of Greenland. The data were delivered to both the National Geospatial Agency and the Land Processes Distributed Active Archive Center



at the US Geological Survey's EROS (Earth Resources Observation and Science) Data Center in Sioux Falls, South Dakota, for distribution to the public. The maps can be downloaded from their Web site (<http://srtm.usgs.gov/>) at no charge, and they are consistently the most popular data set in their archive.

Elevation accuracy was determined by comparing the mission's map to other higher-resolution elevation maps. Results confirmed the findings of the National Geospatial-Intelligence Agency and the US Geological Survey that Shuttle Radar Topography Mission data exceeded their 16-m (52-ft) height accuracy specification by at least a factor of 3.

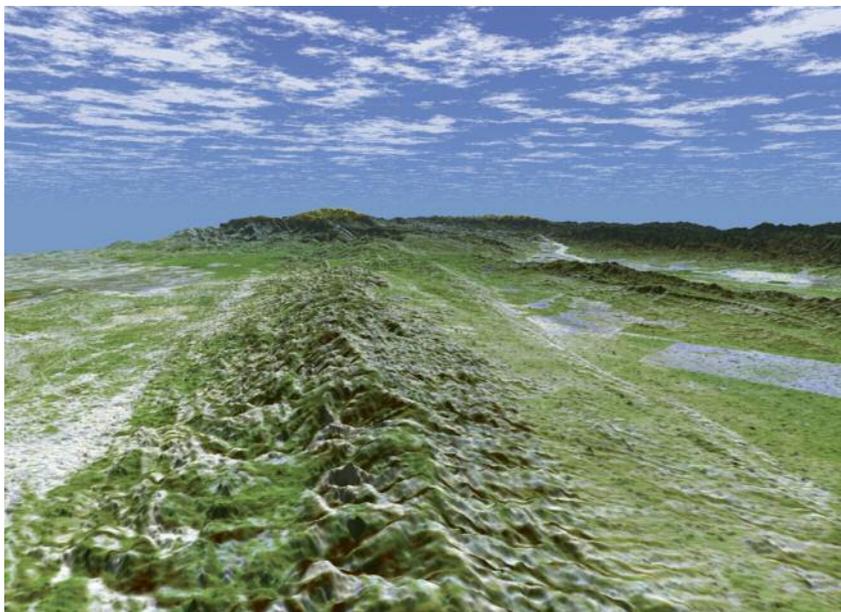
In all, the Shuttle Radar Topography Mission successfully imaged 80% of Earth's landmass and produced topographic maps 30 times as precise as the best maps available at that time.

**Charles Elachi, PhD**  
 Director of Jet Propulsion Laboratory  
 California Institute of Technology.



*"The Space Shuttle played a key role, as the orbiting platform, in advancing the field of radar observation of the Earth. Five flights were conducted between 1981 and 2004, each one with successively more capability. Probably the two most dramatic advances occurred with: 1) the SIR-C\* flight, which demonstrated for the first time 'color' imaging radars with multifrequency/multi-polarization capability, and it is still considered the 'gold standard' for later missions; and 2) the Shuttle Radar Topography Mission flight, which revolutionized topographic mapping by acquiring global digital topography data using interferometric radar. These missions were enabled by the volumetric and lift capability of the shuttle. These two advances in our ability to map the Earth will go down in history as two of the most important contributions of the shuttle to the field of Earth Science."*

\* Shuttle Imaging Radar-C



*US: California's San Andreas fault (1,200 km [800 miles]) is one of the longest faults in North America. This view of a section of it was generated using a Shuttle Radar Topographic Mapping elevation model and draped with a color satellite image. The view shows the fault as it cuts along the base of Temblor Range near Bakersfield, California.*

## Summary

The successful shuttle radar missions demonstrated the capabilities of Earth mapping and paved the way for the Shuttle Radar Topography Mission. This mission was bold and innovative, and resulted in vast improvement by acquiring a new topographic data set for global mapping. It was an excellent example of a mission that brought together the best engineering and the best science minds to provide uniform accuracy elevation information for users worldwide. This success has been enshrined at the Smithsonian Air and Space Museum's Udvar-Hazy Center in Virginia, where the radar mast and outboard systems are displayed.



# Astronaut Health and Performance

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*Human travel to Mars and beyond is no longer science fiction. Through shuttle research we know how the body changes, what we need to do to fix some of the problems or—better yet—prevent them, the importance of monitoring health, and how to determine the human body's performance through the various sequences of launch, spaceflight, and landing. Basically, we understand how astronauts keep their performance high so they can be explorers, scientists, and operators.*

*Astronauts change physically during spaceflight, from their brain, heart, blood vessels, eyes, and ears and on down to their cells. Many types of research studies validated these changes and demonstrated how best to prevent health problems and care for the astronauts before, during, and after spaceflight.*

*During a shuttle flight, astronauts experienced a multitude of gravitational forces. Earth is 1 gravitational force (1g); however, during launch, the forces varied from 1 to 3g. During a shuttle's return to Earth, the forces varied from nearly zero to 1.6g, over approximately 33 minutes, during the maneuvers to return. In all, the shuttle provided rather low gravitational forces compared with other rocket-type launches and landings.*

*The most pervasive physiological human factor in all spaceflight, however, is microgravity. An astronaut perceives weightlessness and floats along with any object, large or small. The microgravity physiological changes affect the human body, the functions within the space vehicle, and all the fluids, foods, water, and contaminants.*

*We learned how to perform well in this environment through the Space Shuttle Program. This information led to improvements in astronauts' health care not only during shuttle flights but also for the International Space Station (ISS) and future missions beyond low-Earth orbit. Shuttle research and medical care led directly to improved countermeasures used by ISS crew members. No shuttle mission was terminated due to health concerns.*



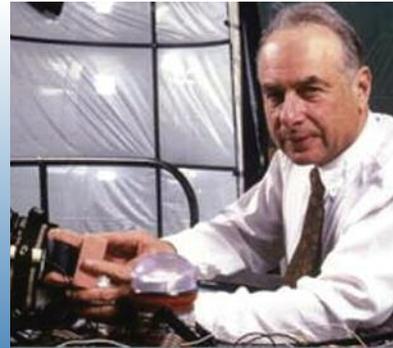
## How Humans Adapt to Spaceflight: Physiological Changes

### Vision, Orientation, and Balance Change in Microgravity

Gravity is critical to our existence. As Earthlings, we have come to rely on Earth's gravity as a fundamental reference that tells us which way is down. Our very survival depends on our ability to discern down so that we can walk, run, jump, and otherwise move about without falling. To accomplish this, we evolved specialized motion-sensing receptors in our inner ears—receptors that act like biological guidance systems. Among other things, these receptors sense how well our heads are aligned with gravity. Our brains combine these data with visual information from our eyes, pressure information from the soles of our feet (and the seats of our pants), and position and loading information from our joints and muscles to continuously track the orientation of our bodies relative to gravity. Knowing this, our brains can work out the best strategies for adjusting our muscles to move our limbs and bodies about without losing our balance. And, we don't even have to think about it.

At the end of launch phase, astronauts find themselves suddenly thrust into the microgravity environment. Gravity, the fundamental up/down reference these astronauts relied on throughout their lives for orientation and movement, suddenly disappears. As you might expect, there are a number of immediate consequences. Disorientation, perceptual illusions, motion sickness, poor eye-head/eye-hand coordination, and whole-body movements are issues each astronaut has to deal with to some degree.

**Laurence Young, ScD**  
Principal investigator or coinvestigator on seven space missions, starting with STS-9 (1983). Alternate payload specialist on STS-58 (1993).  
Founding director of the National Space Biomedical Research Institute. Apollo Program professor of astronautics and professor of health sciences and technology at Massachusetts Institute of Technology.



*"The Space Shuttle Program provided a golden era for life sciences research. The difference between science capabilities on spacecraft before and after the Space Shuttle is enormous: it was like doing science in a telephone booth in the Gemini-Apollo era while shuttle could accommodate a school-bus-size laboratory. This significantly added to the kind of research that could be done in space. We had enormous success in life sciences, especially with the Spacelabs, for quality of instrumentation, their size, and opportunity for repeated measurements on the astronauts on different days of flight and over many different flights including Space Life Sciences flights 1 and 2 and ending with Neurolab.*

*"Our research led to a much more complete understanding of the neurovestibular changes in spaceflight and allowed us to know what issues require countermeasures or treatment, such as space motion sickness, as well as what research needed to continue in Earth laboratories, such as the role of short radius centrifuges for intermittent artificial gravity to support a Mars exploration mission."*

One thing we learned during the shuttle era, though, is that astronauts' nervous systems adapt very quickly. By the third day of flight, most crew members overcame the loss of gravitational stimulation. Beyond that, most exhibited few functionally significant side effects. The downside to this rapid adaptation was that, by the time a shuttle mission ended and the astronauts returned to Earth, they had forgotten how to use gravity for orientation and movement. So, for the first few days after return, they suffered again from a multitude of side effects similar to those experienced at the beginning of spaceflight. During the Earth-readaptation period, these postflight affects limited some types of

physical activities, such as running, jumping, climbing ladders, driving automobiles, and flying planes.

The Space Shuttle—particularly when carrying one of its Spacelab or Spacehab modules and during the human-health-focused, extended-duration Orbiter medical missions (1989 through 1995)—provided unique capabilities to study neurological adaptation to space. By taking advantage of the shuttle's ability to remove and then reintroduce the fundamental spatial orientation reference provided by gravity, many researchers sought to understand the brain mechanisms responsible for tracking and responding to this



stimulus. Other researchers used these stimuli to investigate fundamental and functional aspects of neural adaptation, while others focused on the operational impacts of these adaptive responses with an eye toward reducing risks to space travelers and enabling future missions of longer duration.

## **Space Motion Sickness**

### ***What Is Space Motion Sickness?***

Many people experience motion sickness while riding in vehicles ranging from automobiles to airplanes to boats to carnival rides. Its symptoms include headache, pallor, fatigue, nausea, and vomiting. What causes motion sickness is unknown, but it is clearly related to the nervous system and almost always involves the specialized motion-sensing receptors of the inner ear, known as the vestibular system.

The most popular explanation for motion sickness is the sensory-conflict theory. This theory follows from observations that in addition to planning the best strategies for movement control, the brain also anticipates and tracks the outcome of the movement commands it issues to the muscles. When the tracked outcome is consistent with the anticipated outcome, everything proceeds normally; however, when the tracked outcome is inconsistent, the brain must take action to investigate what has gone wrong. Sensory conflict occurs when some of the sensory information is consistent with the brain's anticipated outcome and some information is inconsistent. This might occur in space, for example, when the brain commands the neck muscles to tilt the head. The visual and neck joint receptors would provide immediate feedback indicating that the head has tilted, but because gravity has been reduced, some of the anticipated signals from the inner ear would not arrive. Initially, this would cause confusion,

disorientation, and motion sickness symptoms. Over time, however, the brain would learn not to anticipate this inner-ear information during head tilts and the symptoms would abate.

### ***How Often Do Astronauts Have Space Motion Sickness?***

Many astronauts report motion sickness symptoms just after arrival in space and again just after return to Earth. For example, of the 400 crew members who flew on the shuttle between 1981 and 1998, 309 reported at least some motion sickness symptoms, such as stomach awareness, headache, drowsiness, pallor, sweating, dizziness, and, of course, nausea and vomiting. For most astronauts, this was a short-term problem triggered by the loss of gravity stimuli during ascent to orbit and, again, by the return of gravity stimuli during descent back to Earth. It usually lasted only through the few days coinciding with neural adaptations to these gravity transitions. While the symptoms of space motion sickness were quite similar to other types of motion sickness, its incidence was not predicted by susceptibility to terrestrial forms,

such as car sickness, sea sickness, air sickness, or sickness caused by carnival rides. To complicate our understanding of the mechanisms of space motion sickness further, landing-day motion sickness was not even predicted by the incidence or severity of early in-flight motion sickness. The only predictable aspect was that repeat flyers usually had fewer and less severe symptoms with each subsequent flight.

### ***How Do Astronauts Deal With Space Motion Sickness?***

Crew members can limit head movements during the first few days of microgravity and during return to Earth to minimize the symptoms of space motion sickness. For some astronauts, drugs are used to reduce the symptoms. Promethazine-containing drugs emerged as the best choice during the early 1990s, and were frequently used throughout the remaining shuttle flights. Scientists also investigated preflight adaptation training in devices that simulate some aspects of the sensory conflicts during spaceflight, but more work is necessary before astronauts can use this approach.



*Some crew members experience height vertigo or acrophobia during extravehicular activities. Astronaut Stephen Robinson is anchored by a foot restraint on the International Space Station Robotic Arm during STS-114 (2005).*



**Dafydd (Dave) Williams, MD**  
Canadian astronaut on STS-90 (1998)  
and STS-118 (2007).



*“Humans adapt remarkably well to the physiologic challenges associated with leaving the Earth’s gravitational environment. For me, these started at main engine cutoff. After 7 minutes of the 8½-minute ride, G forces pushed me like an elephant sitting on my chest. The crushing pressure resolved as I was thrown forward against my harness when the main engines shut down. This created a sense of tumbling, head over heels, identical to performing somersaults as a child. I pulled myself down in the shuttle seat to re-create the gravitational sense of sitting in a chair and the tumbling stopped. I had experienced my first illusion of spaceflight!*”

*“On the first day, many changes took place. My face felt puffy. I had a mild headache. Over the first few days, I experienced mild low back pain. Floating freely inside the shuttle with fingertip forces gently propelling us on a somewhat graceful path reminded me of swimming underwater—with the notable absence of any resistance.*”

*“During re-entry into the Earth’s atmosphere, I felt the forces of gravity gradually building. Standing on the middeck after landing, I felt gravitationally challenged. As I walked onto the crew transfer vehicle I felt as though my arms weighed twice what they normally do. Moving my head created an instant sense of vertigo.*”

*“On my second spaceflight, when I arrived in space it seemed like I had never left and as I floated gracefully, looking back at Earth, it reminded me that I will always remain a spacefarer at heart.”*

### **Spatial Disorientation: Which Way Is Down?**

Astronauts entering the microgravity environment of orbital spaceflight for the first time report many unusual sensations. Some experience a sense of sustained tumbling or inversion (that is, a feeling of being upside down). Others have difficulty accepting down as being the direction one’s feet are pointing, preferring instead to consider down in terms of the module’s orientation during preflight training on the ground.

Almost all have difficulty figuring out how much push-off force is necessary to move about in the vehicle. While spacewalking (i.e., performing extravehicular activities [EVAs]), many astronauts report height vertigo—a sense of dizziness or spinning—that is often experienced by individuals on Earth when looking down from great heights. Some astronauts also experienced transient acrophobia—an overwhelming fear of falling toward Earth—which can be terrifying.

After flight, crew members also experience unusual sensations. For example, to many crew members everyday objects (e.g., apples, cameras) feel surprisingly heavy. Also, when walking up stairs, many experience the sensation that they are pushing the stairs down rather than pushing their bodies up. Some feel an overwhelming sense of translation (sliding to the side) when rounding corners in a vehicle. Many also have difficulty turning corners while walking, and some experience difficulty while bending over to pick up objects. Early after return to Earth, most are unable to land from a jump; many report a sensation that the ground is coming up rapidly to meet them. For the most part, all of these sensations abate within a few days; however, there have been some reports of “flashbacks” occurring, sometimes even weeks after a shuttle mission.

### **Eye-Hand Coordination: Changes in Visual Acuity and Manual Control**

Manual control of vehicles and other complex systems depends on accurate eye-hand coordination, accurate perception of spatial orientation, and the ability to anticipate the dynamic response of the vehicle or system to manual inputs. This function was extremely important during shuttle flights for operating the Shuttle Robotic Arm, which required high-level coordination through direct visual, camera views, and control feedback. It was also of critical importance to piloting the vehicle during rendezvous, docking, re-entry, and landing.

Clear vision begins with static visual acuity (that is, how well one can see an image when both the person and the image are stationary). In most of our daily activities, however, either we are



## Eye-Hand Coordination

Catching a ball is easy for most people on Earth. Yet, we don't usually realize how much work our brains do to predict when and where the ball will come down, get our hand to that exact place at the right time, and be sure our fingers grab the ball when it arrives.

Because of the downward acceleration caused by gravity, the speed of a falling object increases on Earth. Scientists think that the brain must anticipate this to be able to catch a ball. Objects don't fall in space, however. So, scientists wondered how well people could catch objects without gravity. To find out, astronauts

were asked to catch balls launched from a spring-loaded canon that "dropped" them at a constant speed rather than a constant acceleration as on Earth. In flight, the astronauts always caught the balls, but their timing was a little bit off. They reacted as if they expected the balls to move faster than they did, suggesting that their brains were still anticipating the effects of gravity. The astronauts eventually adapted, but some of the effects were still evident after 15 days in space. After flight, the astronauts were initially surprised by how fast the balls fell, but they readapted very quickly. This work showed that, over time in microgravity, astronauts could make changes in their eye-hand coordination, but that it took time after a gravity transition for the brain to accurately anticipate mechanical actions in the new environment.



*Payload specialist James Pawelczyk, STS-90 (1998).*

moving or the object we wish to see is moving. Under these dynamic visual conditions, even people with 20/20 vision will see poorly if they can't keep the image of interest stabilized on their retinas. To do this while walking, running, turning, or bending over, we have evolved complex neural control

systems that use information from the vestibular sensors of the inner ear to automatically generate eye movements that are equal and opposite to any head movements. On Earth, this maintains a stable image on the retina whenever the head is moving.

Since part of this function depends on how the inner ear senses gravity, scientists were interested in how it changes in space. Many experiments performed during and just after shuttle missions examined the effects of spaceflight on visual acuity. Static visual acuity changed mildly, mainly because the headward fluid shifts during flight cause the shape of the eyes to change. Dynamic visual acuity, on the other hand, was substantially disrupted early in flight and just after return to Earth. Even for simple dynamic vision tasks, such as pursuing a moving target without moving the head, eye movements were degraded. But the disruption was found to be greatest when the head was moving, especially in the pitch plane (the plane your head moves in when you nod it to indicate "yes"). Scientists found that whether pursuing a target, switching vision to a new target of interest (the source of a sudden noise, for instance), or tracking a stationary target while moving (either voluntarily or as a result of vehicle motion), eye movement control was inaccurate whenever the head was moving.

Vision (eye movements) and orientation perceptions are disrupted during spaceflight. Scientists found that some kinds of anticipatory actions are inaccurate during flight. The impact of these changes on shuttle operations was difficult to assess. For example, while it appears that some shuttle landings were not as accurate as preflight landings in the Shuttle Training Aircraft, many confounding factors (such as crosswinds and engineering anomalies) precluded rigorous scientific evaluation. It appears that the highly repetitive training crew members received just before a shuttle mission might have helped offset some of the physiological changes during the flight. Whether the



positive effects of this training will persist through longer-duration flights is unknown. At this point, training is the only physiological countermeasure to offset these potential problems.

### Postflight Balance and Walking

When sailors return to port following a long sea voyage, it takes them some time to get back their “land legs.” When astronauts returned to Earth following a shuttle mission, it took them some time to get back their “ground legs.” On

landing day, most crew members had a wide-based gait, had trouble turning corners, and could not land from a jump. They didn’t like bending over or turning their heads independent of their torsos. Recovery usually took about 3 days; but the more time the crew member spent in microgravity, the longer it took for his or her balance and coordination to return to normal. Previous experience helped, though; for most astronauts, each subsequent shuttle flight resulted in fewer postflight effects and a quicker recovery.

Scientists performed many experiments before and after shuttle missions to understand the characteristics of these transient postflight balance and gait disorders. By using creative experimental approaches, they showed that the changes in balance control were due to changes in the way the brain uses inner-ear information during spaceflight. As a result, the crew members relied more on visual information and body sense information from their ankle joints and the bottoms of their feet just after flight. Indeed, when faced with a dark environment (simulated by closing their eyes), the crew members easily lost their balance on an unstable surface (like beach sand, deep grass, or a slippery shower floor), particularly if they made any head movements. As a result, crew members were restricted from certain activities for a few days after shuttle flights to help them avoid injuring themselves. These activities included the return to flying aircraft.

In summary, experiments aboard the Space Shuttle taught us many things about how the nervous system uses gravity, how quickly the nervous system can respond to changes in gravity levels, and what consequences flight-related gravity changes might have on the abilities of crew members to perform operational activities. We know much more now than we did when the Space Shuttle Program started. But, we still have a lot to learn about the impacts of long-duration microgravity exposures, the effects of partial gravity environments, such as the moon and Mars, and how to develop effective physiological countermeasures to help offset some of the undesirable consequences of spaceflight on the nervous system. These will need to be tackled for space exploration.

**Balance: Eye, Ear, and Brain Working in Concert**

Adapted from an illustration by William Scavone, Kestrel Illustration.

*For us to see clearly, the image of interest must be focused precisely on a small region of the retina called the fovea. This is particularly challenging when our heads are moving (think about how hard it is to make a clear photograph if your camera is in motion). Fortunately, our nervous systems have evolved very effective control loops to stabilize the visual scene in these instances. Using information sensed by the vestibular systems located in our inner ears, our brains quickly detect head motion and send signals to the eye muscles that cause compensatory eye movements. Since the vestibular system senses gravity as well as head motion, investigators performed many experiments aboard the shuttle to determine the role of gravity in the control of eye movements essential for balance. They learned that the eye movements used to compensate for certain head motions were improperly calibrated early in flight, but they eventually adapted to the new environment. Of course, after return to Earth, this process had to be reversed through a readaptation process.*



## Sleep Quality and Quantity on Space Shuttle Missions

Many people have trouble sleeping when they are away from home or in unusual environments. This is also true of astronauts. When on a shuttle mission, however, astronauts had to perform complicated tasks requiring optimal physical and cognitive abilities under sometimes stressful conditions.

Astronauts have had difficulty sleeping from the beginning of human spaceflight. Nearly all Apollo crews reported being tired on launch day and many gave accounts of sleep disruption throughout the missions, including some reporting continuous sleep periods lasting no more than 3 hours. Obtaining adequate sleep was also a serious challenge for many crew members aboard shuttle missions.

## Environmental Factors

Several factors negatively affect sleep: unusual light-dark cycles, noise, and unfavorable temperatures. All of these factors were present during shuttle flights and made sleep difficult for crew members. Additionally, some crew members reported that work stress further diminished sleep.

When astronauts completed a daily questionnaire about their sleep, almost 60% of the questionnaires indicated that sleep was disturbed during the previous night. Noise was listed as the reason for the sleep disturbance approximately 20% of the time. High levels of noise negatively affect both slow-wave (i.e., deep sleep important for physical restoration) and REM (Rapid Eye Movement) sleep (i.e., stage at which most dreams occur and

important for mental restoration), diminishing subsequent alertness, cognition, and performance. A comfortable ambient temperature is also important for promoting sleep. On the daily questionnaire, approximately 15% of the disturbances were attributed to the environment being too hot and approximately 15% of the disturbances were attributed to it being too cold. Thus, the shuttle environment was not optimal for sleep.

## Circadian Rhythms

Appropriately timed circadian rhythms are important for sleep, alertness, performance, and general good health. Light is the most important time cue to the body's circadian clock, which has a natural period of about 24.2 hours. Normally, individuals sleep when it is dark and are awake when it is light.

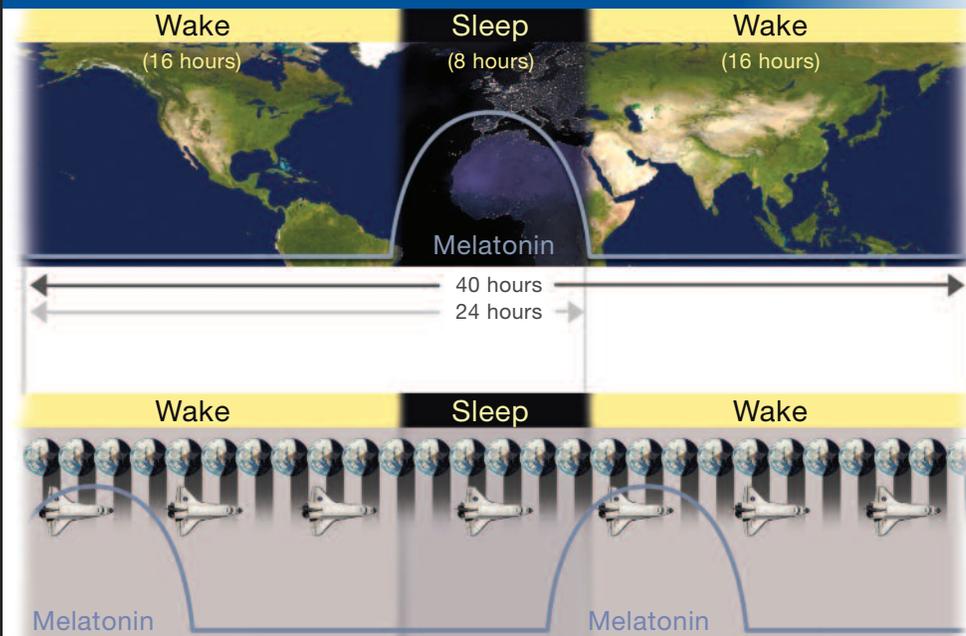
### Comparison of Earth and Space Sleep Cycles

#### Earth Conditions

On a 24-hour external light-dark cycle, the body's circadian clock remains properly synchronized (e.g., hormones like melatonin are released at the appropriate time).

#### Space Conditions

On the Orbiter's 90-minute light-dark cycle, weak interior ambient light may not sufficiently cue the body's circadian clock, which may then become desynchronized (e.g., inappropriately timed hormone release).





This 24-hour pattern resets the body's clock each day and keeps all of the body's functions synchronized, maximizing alertness during the day and consolidating sleep at night. Unlike the 24-hour light-dark cycle that we experience on Earth, shuttle crew members experience 90-minute light-dark cycles as they orbited the Earth.

Not only is the timing of light unsuitable, but the low intensity of the light aboard the shuttle may have contributed to circadian misalignment. Light levels were measured in the various compartments of the shuttle during Space Transportation System (STS)-90 Neurolab (1998) and STS-95 (1998) missions. In the Spacelab, light levels were constant and low (approximately 10 to 100 lux) during the working day. In the middeck, where the crew worked, ate, and slept, the light levels recorded were relatively constant and very dim (1 to 10 lux). Laboratory data showed that these light levels are insufficient to entrain the human circadian pacemaker to non-24-hour sleep-wake schedules. Normal room lighting (200 to 300 lux) would be required to keep the circadian system aligned under 24-hour light-dark cycles.

Crew members also were often scheduled to work on 23.5-hour days or had to shift their sleep-wake schedule several hours during flight. Moreover, deviations from the official schedule were frequently required by operational demands typical of space exploration. Therefore, the crew members' circadian rhythms often became misaligned, resulting in them having to sleep during a time when their circadian clock was promoting alertness, much as a shift worker on Earth.

Actually, difficulties with sleep began even before the shuttle launched. Often in the week prior to launch

crew members had to shift their sleep-wake schedule, sometimes up to 12 hours. This physiological challenge, associated with sleep disruption, created "fatigue pre-load" before the mission even began.

All US crew members participated in the Crew Health Stabilization Program where they were housed together for 7 days prior to launch to separate them from potential infectious disease from people and food. During this quarantine period, scientists at Harvard Medical School, in association with NASA, implemented a bright-light treatment program for crew members of STS-35 (1990), the first Space Shuttle mission requiring both dual shifts and a night launch.

Scheduled exposure to bright light (about 10,000 lux—approximately the brightness at sunrise), at appropriate times throughout the prelaunch period at Johnson Space Center and Kennedy Space Center, was used to prepare shuttle crew members of the Red Team of STS-35 for both their night launch and their subsequent night-duty shift schedule in space. A study confirmed that the prescribed light exposure during the prelaunch quarantine period successfully induced circadian realignment in this crew. Bright lights were installed at both centers' crew quarters in 1991 for use when shuttle flights required greater than a 3-hour shift in the prelaunch sleep-wake cycle.

### ***Studies of Sleep in Space***

NASA studied sleep quality and quantity and investigated the underlying physiological mechanisms associated with sleep loss as well as countermeasures to improve sleep and ultimately enhance alertness and performance in space. Scientists conducted a comprehensive sleep

study on STS-90 and STS-95 missions using full polysomnography, which monitors brain waves, tension in face muscles, and eye movements, and is the "gold standard" for evaluating sleep. Scientists also made simultaneous recordings of multiple circadian variables such as body temperature and cortisol, a salivary marker of circadian rhythms. This extensive study included performance assessments and the first placebo-controlled, double-blind clinical trial of a pharmaceutical (melatonin) during spaceflight. Crew members on these flights experienced circadian rhythm disturbances, sleep loss, and decrements in neurobehavioral performance.

For another experiment, crew members wore a watch-like device, called an actigraph, on their wrists to monitor sleep. The actigraph contained an accelerometer that measured wrist motion. From that recorded motion scientists were able to use software algorithms to estimate sleep duration. Fifty-six astronauts (approximately 60% of the Astronaut Corps between 2001 and 2010) participated in this study. Average nightly sleep duration across multiple shuttle missions was approximately 6 hours. This level of sleep disruption has been associated with cognitive performance deficits in numerous ground-based laboratory and field studies.

Pharmaceuticals were the most widespread countermeasure for sleep disruption during shuttle flights. Indeed, more than three-quarters of astronauts reported taking sleep medications during missions. Astronauts took sleep medications during flight half the time. Wake-promoting therapeutics gained in popularity as well, improving alertness after sleep-disrupted nights.



**Richard Searfoss**

Colonel, US Air Force (retired).  
Pilot for STS-58 (1993) and  
STS-76 (1996).  
Commander for STS-90 (1998).



**Perspectives on  
NeuroLab**

*"I was privileged to  
command STS-90*

*NeuroLab, focusing on the effects of weightlessness on the brain and nervous system. Although my technical background is in engineering and flight test, it was still incredibly rewarding to join a dedicated team that included not just NASA but the National Institutes of Health and top researchers in the world to strive with disciplined scientific rigor to really understand some of the profound changes to living organisms that take place in the unique microgravity environment. I viewed my primary role as science enabler, calling on my operational experience to build the team, lead the crew, and partner with the science community to accomplish the real 'mission that mattered.'*

*"Even though at the time STS-90 flew on Columbia humans had been flying to space nearly 40 years, much of our understanding of the physiological effects was still a mystery. NeuroLab was extremely productive in unveiling many of those mysteries. The compilation of peer-reviewed scientific papers from this mission produced a 300-page book, the only such product from any Space Shuttle mission. I'll leave it to the scientists to testify to the import, fundamental scientific value, and potential for Earth-based applications from NeuroLab. It's enough for me to realize that my crew played an important role in advancing science in a unique way.*

*"With STS-90 as the last of 25 Spacelab missions, NASA reached a pinnacle of overall capability to meld complex, leading-edge science investigations with the inherent challenges of operating in space. Building on previous Spacelab flights, NeuroLab finished up the Spacelab program spectacularly, with scientific results second to none. What a joy to be part of that effort! It was unquestionably the honor of my professional life to be a member of the NeuroLab team in my role as commander."*

Although sleep-promoting medication use was widespread in shuttle crew members, investigations need to continue to determine the most

acceptable, feasible, and effective methods to promote sleep in future missions. Sleep monitoring is ongoing in crew members on the International

Space Station (ISS) where frequent shifts in the scheduled sleep-wake times disrupt sleep and circadian alignment. Sleep most certainly will also be an issue when space travel continues beyond low-Earth orbit. Private sleep quarters will probably not be available due to space and mass issues. Consequently, ground-based studies continue to search for the most effective, least invasive, and least time-consuming countermeasures to improve sleep and enhance alertness during spaceflight. Currently, scientists are trying to pinpoint the most effective wavelength of light to use to ensure alignment of the circadian system and improve alertness during critical tasks.

**Spaceflight Changes Muscle**

Within the microgravity environment of space, astronauts' muscles are said to be "unweighted" or "unloaded" because their muscles are not required to support their body weight. The unloading of skeletal muscle during spaceflight, in what is known as "muscle atrophy," results in remodeling of muscle (atrophic response) as an adaptation to the spaceflight. These decrements, however, increase the risk of astronauts being unable to adequately perform physically demanding tasks during EVAs or after abrupt transitions to environments of increased gravity (such as return to Earth at the end of a mission).

A similar condition, termed "disuse muscle atrophy," occurs any time muscles are immobilized or not used as the result of a variety of medical conditions, such as wearing a cast or being on bed rest for a long time. Space muscle research may provide a better understanding of the mechanisms underlying disuse muscle atrophy, which may enable better management



of these patients. In the US human space program, the only tested in-flight preventive treatment for muscle atrophy has been physical exercise. In-flight exercise hardware and protocols varied from mission to mission, somewhat dependent on mission duration as well as on the internal volume of the spacecraft. Collective knowledge gained from these shuttle missions aided in the evolution of exercise hardware and protocols to prevent spaceflight-induced muscle atrophy and the concomitant deficits in skeletal muscle function.

### ***How Was Muscle Atrophy Measured, and What Were the Results?***

#### ***Leg and Back Muscle Size Decreases***

Loss of muscle and strength in the lower extremities of astronauts was initially found in the Gemini (1962-1966) and Apollo missions (1967-1972) and was further documented in the first US space station missions (Skylab, 1973-1974) of 28, 59, and 84 days' duration. NASA calculated crude muscle volumes by measuring the circumference of the lower and upper legs and arms at multiple sites.

For shuttle astronauts, more sophisticated, accurate, and precise measures of muscle volume were made by magnetic resonance imaging (MRI). MRI is a common diagnostic medical procedure used to image patient's internal organs that was adapted to provide volume measurements of a crew member's lower leg, thigh, and back muscles before and after flight. The leg muscle volume was evaluated in eight astronauts (seven males and one female, age range 31 to 39 years) who flew on either one of two 9-day missions. Scientists obtained MRI scans of multiple leg cross sections prior to flight and compared them to scans obtained at 2 to 7 days after

flight. The volumes of various leg muscles were reduced by about 4% to 6% after spaceflight. In another study of longer missions (9 to 16 days' duration—two males and one female, mean age 41 years), the losses were reported to be greater, ranging from 5.5% to 15.9% for specific leg muscles. This study found that daily volume losses of leg muscles normalized for duration of flight were from 0.6% to 1.04% per mission day.

#### ***Muscle Strength Decreases***

Decreases in muscle strength persisted throughout the shuttle period in spite of various exercise prescriptions. Measurements of muscle strength, mass, and performance helped NASA determine the degree of muscle function loss and assess the efficacy of exercise equipment and determine whether exercise protocols were working as predicted.

Muscle strength, measured with a dynamometry (an instrument that measures muscle-generated forces, movement velocity, and work) before launch and after landing consistently showed loss of strength in muscles that extend the knee (quadriceps muscles) by up to 12% and losses in trunk flexor strength of as much as 23%. The majority of strength and endurance losses occurred in the trunk and leg muscles (the muscle groups that are active in normal maintenance of posture and for walking and running) with little loss noted in upper body and arm muscle strength measurements. In contrast, four STS-78 (1996) astronauts had almost no decrease in calf muscle strength when they participated voluntarily in high-volume exercise in combination with the in-flight, experiment-specific muscle strength performance measurements. This preliminary research suggested that such

exercises may prevent loss of muscle function leading to implementation of routine combined aerobic and resistive exercise for ISS astronauts.

#### ***Muscle Fiber Changes in Size and Shape***

An "average" healthy person has roughly equal numbers of the two major muscle fiber types ("slow" and "fast" fibers). Slow fibers contract (shorten) slowly and have high endurance (resistance to fatigue) levels. Fast fibers contract quickly and fatigue readily. Individual variation in muscle fiber type composition is genetically (inherited) determined. The compositional range of slow fibers in the muscles on the front of the thigh (quadriceps muscles) in humans can vary between 20% and 95%, a percentage found in many marathon runners. On the other hand, a world-class sprinter or weight lifter would have higher proportions of fast fibers and, through his or her training, these fibers would be quite large (higher cross-sectional diameter or area). Changing the relative proportions of the fiber types in muscles is possible, but it requires powerful stimulus such as a stringent exercise program or the chronic unloading profile that occurs in microgravity. NASA was interested in determining whether there were any changes in the sizes or proportions of fiber types in astronauts during spaceflight.

In the only biopsy study of US astronauts to date, needle muscle biopsies from the middle of the vastus lateralis muscle (a muscle on the side of the thigh) of eight shuttle crew members were obtained before launch (3 to 16 weeks) and after landing (within 3 hours) for missions ranging in duration from 5 to 11 days. Three of the eight crew members (five males and three females, age range 33 to 47 years)



flew 5-day missions while the other five crew members completed 11-day flights. Five of the eight crew members did not participate in other medical studies that might affect muscle fiber size and type. NASA made a variety of measurements in the biopsy samples, including relative proportions of the two major muscle fiber types, muscle fiber cross-sectional area by muscle fiber type, and muscle capillary (small blood vessel) density. Slow fiber-type cross-sectional area decreased by 15% as compared to a 22% decrease for fast fiber muscle fibers. Biopsy samples from astronauts who flew on the 11-day mission showed there were relatively more fast fiber types and fewer slow fiber types, and the density of muscle capillaries was reduced when the samples taken after landing were compared to those taken before launch. NASA research suggests that fiber types can change in microgravity due to the reduced loads. This has implications for the type and volume of prescriptive on-orbit exercise.

Research conducted during the shuttle flights provided valuable insight into how astronauts' muscles responded to the unloading experienced while living and working in space. Exercise equipment and specific exercise therapies developed and improved on during the program are currently in use on the ISS to promote the safety and health of NASA crew members.

## **The “Why” and “How” of Exercise on the Space Shuttle**

### ***Why Exercise in Space?***

Just as exercise is an important component to maintain health here on Earth, exercise plays an important role in maintaining astronaut health and fitness while in space. While living in space requires very little effort to

maneuver around, the lack of gravity can decondition the human body.

Knowledge gained during the early years of human spaceflight indicated an adaptation to the new environment. While the empirical evidence was limited, the biomedical data indicated that microgravity alters the musculoskeletal, cardiovascular, and neurosensory systems. In addition, the responses to spaceflight varied from person to person. Space adaptation was highly individualized, and some human systems adjusted at different rates. Overall, these changes were considered to have potential implications on astronaut occupational performance as well as possible impacts to crew health and safety. There was concern that space-related deconditioning could negatively influence critical space mission tasks, such as construction of the space station, repair of the orbiting Hubble Space Telescope, piloting and landing operations, and the ability to egress in an emergency.

Historically, NASA worked on programs to develop a variety of strategies to prevent space deconditioning, thus migrating toward the use of exercise during spaceflight to assure crew member health and fitness. In general, exercise offered a well-understood approach to fitness on Earth, had few side effects, and provided a holistic approach for addressing health and well-being, both physically and psychologically.

NASA scientists conducted experiments in the 1970s to characterize the effects of exercise during missions lasting 28, 56, and 84 days on America's first orbiting space station—Skylab. This was the first opportunity for NASA to study the use of exercise in space. These early observations demonstrated that exercise modalities and intensity could improve the fitness outcomes of

astronauts, even as missions grew in length. Armed with information from Skylab, NASA decided to provide exercise on future shuttle missions to minimize consequences that might be associated with spaceflight deconditioning to guarantee in-flight astronaut performance and optimize postflight recovery.

### ***Benefits of Exercise***

Space Shuttle experience demonstrated that for the short-duration shuttle flights, the cardiovascular adaptations did not cause widespread significant problems except for the feelings of light-headedness—and possibly fainting—in about one-fifth of the astronauts and a heightened concern over irregular heartbeats during spacewalks. During the Space Shuttle Program, however, it became clear from these short-duration missions that exercise countermeasures would be required to keep astronauts fit during long-duration spaceflights. Although exercise was difficult in the shuttle, simple exercise devices were the stationary bike, a rowing machine, and a treadmill. Astronauts, like those from Skylab, found it difficult to raise their heart rate high enough for adequate exercise. NASA demonstrated that in-flight exercise could be performed and helped maintain some aerobic fitness, but much research remained to be done. This finding led to providing the ISS with a bicycle ergometer, a treadmill, and a resistive exercise device to ensure astronaut fitness.

Deconditioning due to a lack of aerobic exercise is a concern in the area of EVAs, as it could keep the astronaut from performing spacewalks and other strenuous activities. Without enough in-flight aerobic exercise, astronauts experienced elevated heart rates and systolic blood pressures.



**Ken Baldwin, PhD**

Principal investigator on three Spacelab missions—STS-40 (1991), STS-58 (1993), and STS-90 (1998)—and a Physiological Anatomical Rodent Experiment. Muscle Team leader, 2001-2009, for the National Space Biomedical Research Institute.



*“The space life sciences missions (STS-40, STS-58, and STS-90) provided a state-of-the-art laboratory away from home that enabled scientists to customize their research studies in ways that were unheard of prior to the Space Shuttle Program. In using such a laboratory, my research generated unique insights concerning the remodeling of muscle structure and function to smaller, weaker, fatigue-prone muscles with a contractile phenotype that was poorly suitable to opposing gravity. These unique findings became the cornerstone of recommendations that I spearheaded to redesign the priority of exercise during spaceflight from one of an aerobic exercise focus (treadmill and cycling exercise) to a greater priority of exercise paradigms favoring heavy-resistance exercise in order to prevent muscle atrophy in microgravity. Additionally, our group also made an important discovery in ground-based research supported by NASA’s National Space Biomedical Research Institute showing that it is not necessarily the contraction mode that the muscles must be subjected to, but rather it is the amount and volume of mechanical force that the muscle must generate within a given contraction mode in order to maintain normal muscle mass. Thus, the early findings aboard the Space Shuttle have served as a monument for guiding future research to expand humankind’s success in living productively on other planets under harsh conditions.”*

The deconditioned cardiovascular system must work harder to do the same or even less work (exercise) than the well-conditioned system.

Exercise capacity was measured preflight on a standard upright bike. Exercise was stepped up every 3 minutes with an increase in workload. Maximal exercise was determined preflight by each astronaut’s maximum volume of oxygen uptake. A conditioned astronaut may have little increase in heart rate above sitting when he

or she is walking slowly. The heart rate and systolic blood pressure (the highest blood pressure in the arteries, just after the heartbeats during each cardiac cycle) increase as the astronaut walks fast or runs until the heart rate cannot increase any more.

In-flight exercise testing showed that crew members could perform at 70% of the preflight maximum exercise level with no significant issues. This allowed mission planners to schedule EVAs and other strenuous activities that did not overtax the astronauts’ capabilities.

**How Astronauts Exercised on the Space Shuttle**

Because of the myriad restrictions about what can be launched within a space vehicle, tremendous challenges exist related to space exercise equipment. Systems need to be portable and lightweight, use minimal electrical power, and take up limited space during use and stowage. In addition, operation of exercise equipment in microgravity is inherently different than it is on Earth. Refining the human-to-machine interfaces for exercise in space was a challenging task tested throughout the shuttle missions. Providing exercise concepts with the appropriate physical training stimulus to maintain astronaut performance that operates effectively in microgravity proved to be a complex issue.

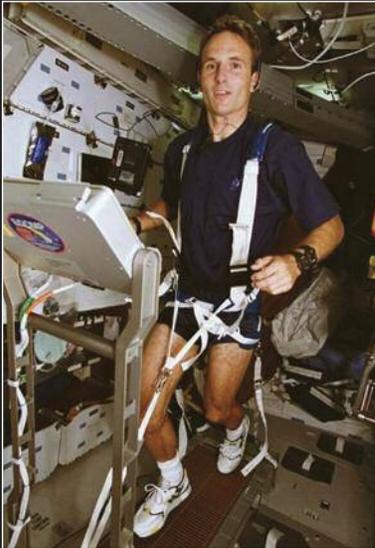
Exercise systems developed for shuttle included: treadmill, cycle ergometer, and rower. The devices offered exercise conditioning that simulated ambulation, cycling, and rowing activities. All exercise systems were designed for operations on the shuttle middeck; however, the cycle could also be used on the flight deck so that astronauts could gaze out the overhead windows during their exercise sessions.

Each of the three systems had its own challenges for making Earth-like exercise feasible while in space within the limits of the shuttle vehicle. Most traditional exercise equipment has the benefit of gravity during use, while spaceflight systems require unique approaches to exercise for the astronaut users. While each system had its unique issues for effective space operations, the exercise restraints were some of the biggest challenges during the program. These restraints included techniques for securing an astronaut to the exercise device itself to allow for effective exercise stimuli.



***“Shuttle left a legacy, albeit incomplete, of the theory and practice for exercise countermeasures in space.”***

*William Thornton, MD, astronaut, principal investigator and original inventor of the shuttle treadmill.*



*The evolution of types of exercise: running, rowing, and cycling from Earth to space configurations. Astronaut Jerry Linenger running during STS-64 (1994), Astronaut Robert Cabana rowing on STS-53 (1992), and Astronaut Catherine Coleman cycling on STS-73 (1995).*

In-flight exercise quality and quantity were measured on all modalities using a commercial heart rate monitor for tracking work intensity and exercise duration. This allowed for a common measure across devices. Heart rate is a quality indicator of exercise intensity and duration (time) is a gauge of exercise quantity—common

considerations used for generating exercise prescriptions. Research showed that target heart rates could be achieved using each of the three types of exercise during spaceflight.

***Treadmill***

Running and walking on a treadmill in the gym can be computer controlled

with exercise profiles that alter speed and grade. The shuttle treadmill had limits to its tread length and speed and had no means for altering grade. Treadmill ambulation required the astronaut to wear a complex over-the-shoulder bungee harness system that connected to the treadmill and held the runner in place during use. Otherwise, the runner would propel off the tread with the first step. While exercise target heart rates were achieved, the treadmill length restricted gait length and the harness system proved quite uncomfortable. This information was captured as a major lesson learned for the development of future treadmill systems for use in space.

***Cycle Ergometer***

The shuttle cycle ergometer (similar to bicycling) operated much like the equipment in a gym. It used a conventional flywheel with a braking band to control resistance via a small motor with a panel that displayed the user’s speed (up to 120 rpm) and workload (up to 350 watts). The restraint system used commercial pedal-to-shoe bindings, or toe clips, that held the user to the cycle while leaning on a back pad in a recumbent position. The cycle had no seat, however, and used a simple lap belt to stabilize the astronaut during aerobic exercise. While the cycle offered great aerobic exercise, it was also used for prebreathe operations in preparation for EVAs. The prebreathe exercise protocol allowed for improved nitrogen release from the body tissues to minimize the risk of tissue bubbling during the EVA that could result in decompression sickness or “the bends.” Exercise accelerated, “washout” nitrogen that may bubble in the tissues during EVA, causing decompression sickness and, thereby, terminating the EVA and risking crew health.



### **Rower**

The rower offered total body aerobic exercise, similar to gym rowers. It also had limited capability for resistance exercise. Similar to the cycle, it was seatless since the body floats. The astronaut's feet were secured with a Velcro® strap onto a footplate that allowed for positioning. The rower used a magnetic brake to generate resistance.

### **Summary**

In summary, exercise during Space Shuttle flights had physical and psychological benefits for astronauts. In general, it showed that astronauts could reduce the deconditioning effects that may alter performance of critical mission tasks using exercise in space, even on the relatively short shuttle missions. As a result, a “Flight Rule” was developed that mandated astronauts exercise on missions longer than 11 days to maintain crew health, safety, and performance.

Each device had the challenge of providing an appropriate exercise stimulus without the benefit of gravity and had a unique approach for on-orbit operations. Engineers and exercise physiologists worked closely together to develop Earth-like equipment for the shuttle environment that kept astronauts healthy and strong.

## **Cardiovascular: Changes in the Heart and Blood Vessels That Affect Astronaut Health and Performance**

The cardiovascular system, including the heart, lungs, veins, arteries, and capillaries, provides the cells of the body with oxygen and nutrients and allows metabolic waste products to be eliminated through the kidneys (as urine) and the gastrointestinal tract. All of this depends on a strong heart

to generate blood pressure and a healthy vascular system to regulate the pressure and distribute the blood, as needed, throughout the body via the blood vessels.

For our purposes, the human body is essentially a column of fluid; the hydrostatic forces that act on this column, due to our upright posture and bipedal locomotion, led to a complex system of controls to maintain—at a minimum—adequate blood flow to the brain.

On Earth, with its normal gravity, all changes in posture—such as when lying down, sitting, or standing as well as changes in activity levels such as through exercising—require the heart and vascular system to regulate blood pressure and distribution by adjusting the heart rate (beats per minute), amount of blood ejected by the heart (or stroke volume), and constriction or dilation of the distributing arteries. These adjustments assure continued consciousness by providing oxygen to the brain or continued ability to work, with oxygen going to the working muscles.

Removing the effects of gravity during spaceflight and restoring gravity after a period of adjustment to weightlessness present significant challenges to the cardiovascular control system. The cardiovascular system is stressed very differently in spaceflight, where body fluids are shifted into the head and upper body and changes in posture do not require significant responses because blood does not drain and pool in the lower body. Although the cardiovascular system is profoundly affected by spaceflight, the basic mechanisms involved are still not well understood.

During the shuttle era, flight-related cardiovascular research focused on topics that could benefit the safety and

well-being of crew members while also revealing the mechanisms underlying the systemic adjustments to spaceflight. NASA researchers studied the immediate responses to the effects of weightlessness during Space Shuttle flights and the well-developed systemic adjustments that followed days and weeks of exposure. Most such research related to the loss of orthostatic tolerance after even brief flights and to the development of potentially detrimental disturbances in cardiac rhythm during longer flights.

Scientists also evaluated the usefulness of several interventions such as exercise, fluid ingestion, and landing-day gravity suits (g-suits) in protecting the astronauts' capacities for piloting the Orbiter—an unpowered, 100-ton glider—safely to a pinpoint landing, and especially for making an unaided evacuation from the Orbiter if it landed at an alternate site in an emergency.

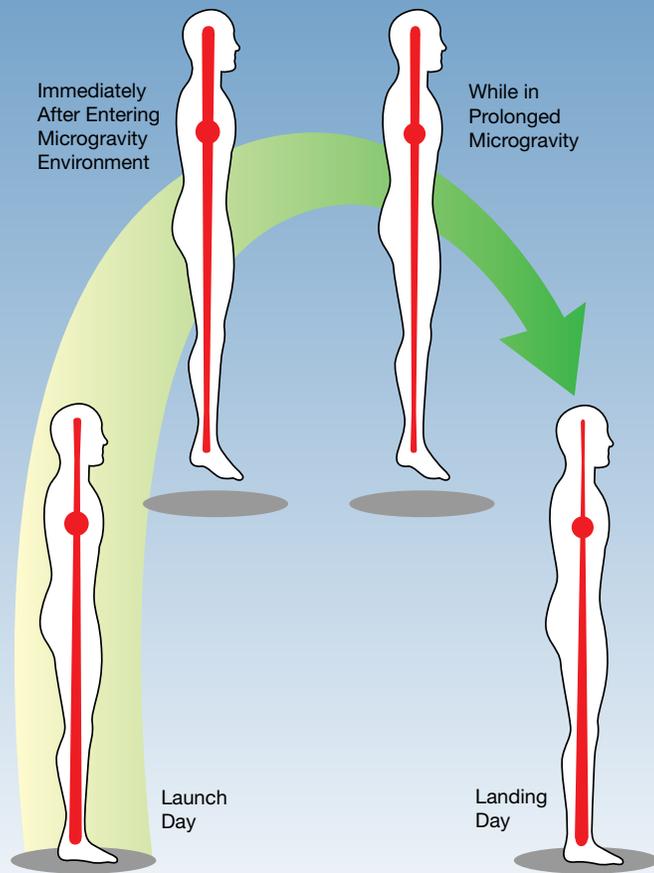
### ***Orthostatic Intolerance: Feeling Light-headed and Fainting on Standing Upright***

One of the most important changes negatively impacting flight operations and crew safety is landing day orthostatic intolerance. Astronauts who have orthostatic intolerance (literally, the inability to remain standing upright) cannot maintain adequate arterial blood pressure and have decreased brain blood levels when upright, and they experience light-headedness and perhaps even fainting. This may impair their ability to stand up and egress the vehicle after landing, and even to pilot the vehicle while seated upright as apparent gravity increases from weightlessness to 1.6g during atmospheric re-entry.

The orthostatic intolerance condition is complicated and multifactorial. Its hallmarks are increased heart rate, decreased systolic blood pressure,



### Blood Volume Changes During Spaceflight



*The distribution of blood changes in microgravity more in the upper torso and less in the legs. At landing, the astronaut is light-headed because of less blood and the pooling of the blood in the feet.*

and decreased stroke volume during 5 minutes of standing shortly after landing. The decrease in blood volume frequently observed is an important initiating event in the etiology of orthostatic intolerance, but it is the subsequent effects and the physiological responses (or lack thereof) to those effects that may result in orthostatic intolerance after shuttle flights. This is highlighted by the fact that while all shuttle crew members who were tested had low blood volume on landing day, only one-quarter of

them developed orthostatic intolerance during standing or head-up tilting.

The group of astronauts that developed orthostatic intolerance lost comparable amounts of plasma (the watery portion of the blood, which the body can adjust quickly) to the group that did not develop orthostatic intolerance. But, the group that was not susceptible had a more pronounced increase in the functioning of the sympathetic nervous system, which is important in responding to orthostatic stress

after returning to Earth. Thus, it is not the plasma volume loss alone that causes light-headedness but the lack of compensatory activation of the sympathetic system.

Another possible mechanism for post-spaceflight orthostatic hypotension (low blood pressure that causes fainting) is cardiac atrophy and the resulting decrease in stroke volume (the amount of blood pushed out of the heart at each contraction). Orthostatic hypotension occurs if the fall in stroke volume overwhelms normal compensatory mechanisms such as an increase in heart rate or constriction in the peripheral blood vessels in the arms, legs, and abdomen.

The vast majority of astronauts have been male. Consequently, any conclusions drawn regarding the physiological responses to spaceflight are male biased. NASA recognized significant differences in how men and women respond to spaceflight, including the effects of spaceflight on cardiovascular responses to orthostatic stress. More than 80% of female crew members tested became light-headed during postflight standing as compared to about 20% of men tested, confirming a well-established difference in the non-astronaut population. This is an important consideration for prevention, as treatment methods may not be equally effective for both genders.

#### *How Can This Risk be Changed?*

While orthostatic intolerance is perhaps the most comprehensively studied cardiovascular effect of spaceflight, the mechanisms are not well understood. Enough is known to allow for the implementation of some countermeasures, yet none of these countermeasures have been completely successful at eliminating spaceflight-induced orthostatic intolerance following spaceflight.



In 1985, ingestion of fluid and salt (or “fluid loading”) prior to landing became a medical requirement through a Flight Rule given the demonstrated benefits and logic that any problem caused—at least in part—by a loss in plasma volume should be resolved—at least in part—by fluid restoration. Starting about 2 hours before landing, astronauts ingest about 1 liter (0.58 oz) of water along with salt tablets. Subsequent refinements to enhance palatability and tolerance include the addition of sweeteners and substitution of bouillon solutions. Of course, any data on plasma volume acquired after 1985 do not reflect the unaltered landing day deficit. But, in spite of the fluid loading, astronauts still returned from shuttle missions with plasma volume deficits ranging from 5% to 19% as well as with orthostatic intolerance.

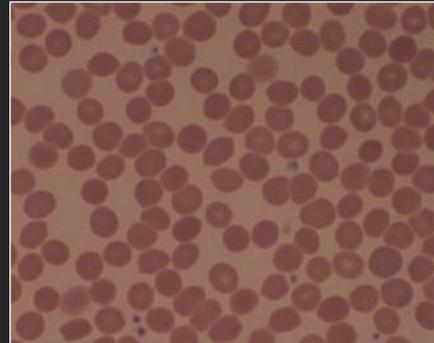
Shuttle astronauts returned home wearing a lower-body counterpressure garment called the anti-g suit. These suits have inflatable bladders at the calves, thighs, and lower abdomen that resist blood pooling in those areas and force the blood toward the head. The bladders can be pressurized from 25 mmHg (0.5 psi) to 130 mmHg (2.5 psi). In addition, ISS crew members landing on the shuttle used recumbent seats (as opposed to the upright seats of the shorter-duration shuttle crews) and only inflated their suit minimally to 25 mmHg (0.5 psi). All astronauts deflated their anti-g suit slowly after the shuttle wheeled to a stop to allow their own cardiovascular systems time to readjust to the pooling effects of Earth’s gravity.

Other treatments for orthostatic intolerance were also evaluated during the program. A technique called “lower body negative pressure,” which used slight decompression of an airtight chamber around the abdomen and legs to pool blood there

## How Red Blood Cells Are Lost in Spaceflight

What do astronauts, people traveling from high altitudes to sea level, and renal (kidney) failure patients have in common?

All experience changes in red blood cell numbers due to changes in the hormone erythropoietin, synthesized in the kidneys.



Red blood cells bring oxygen to tissues. When astronauts enter microgravity or high-altitude residents travel to sea level, the body senses excess red blood cells. High-altitude residents produce an increased number because of decreased ambient oxygen levels but, at sea level, excess cells are not needed. Astronauts experience a 15% decrease in plasma volume as the body senses an increase in red blood cells per volume of blood. In these situations, erythropoietin secretion from the kidneys ceases. Prior to our research, we knew that when erythropoietin secretion stops, the bone marrow stops production of pre red blood cells and an increase in programmed destruction of these cells occurs.

Another function was found in the absence of erythropoietin, the loss of the newly secreted blood cells from the bone marrow—a process called neocytolysis. Since patients with renal failure are unable to synthesize erythropoietin, it is administered at the time of renal dialysis (a process that replaces the lost kidney functions); however, blood levels of erythropoietin fell rapidly between dialysis sessions, and neocytolysis occurs. Thus, the development of long-lasting erythropoietin now prevents neocytolysis in these patients. Erythropoietin is, therefore, important for human health—in space and on Earth—and artificial erythropoietin is essential for renal failure patients.

and thus recondition the cardiovascular system, showed promise in ground studies but was judged too cumbersome and time consuming for routine shuttle use. A much simpler approach used a medication known as fludrocortisone, a synthetic corticosteroid known to increase fluid retention in patients on Earth. It proved unsuccessful, however, when it was not

well-tolerated by crew members and did not produce any differences in plasma volume or orthostatic tolerance.

Thus, the countermeasures tested were not successful in preventing postflight orthostatic intolerance, at least not in an operationally compatible manner. The knowledge gained about spaceflight-induced cardiovascular

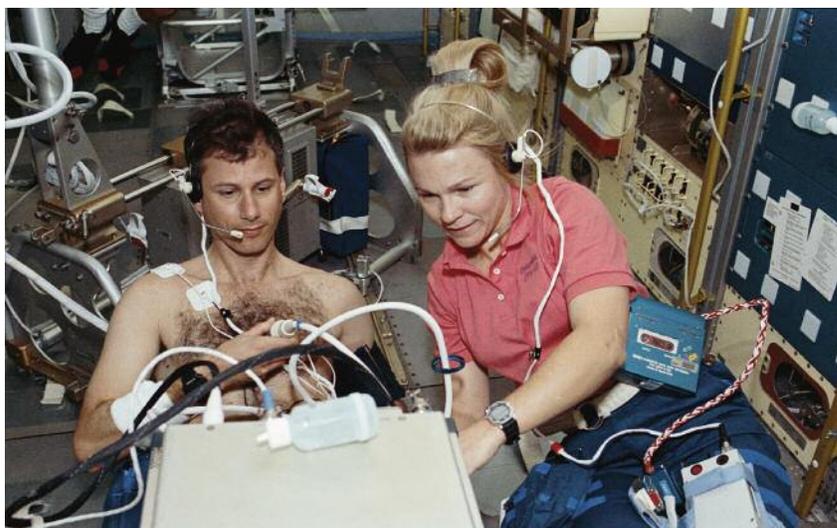


changes and differences between orthostatic tolerance groups, however, provided a base for development of future pharmacological and mechanical countermeasures, which will be especially beneficial for astronauts on long-duration missions on space stations and to other planets.

### **Cardiovascular Changes During Spaceflight**

Headward fluid shift was inferred from reports containing astronaut observations of puffy faces and skinny legs, and was long believed to be the initiating event for subsequent cardiovascular responses to spaceflight. The documentation of this shift was an early goal of Space Shuttle-era investigators, who used several techniques to do so. Direct measurement of peripheral venous blood pressure in an arm vein (assumed to reflect central venous pressure in the heart, an indication of headward fluid shift) was done in 1983 during in-flight blood collections. Actual measurement of central venous pressure was done on a small number of astronauts on dedicated space life sciences Spacelab missions starting in 1991. These studies, and particularly the direct central venous pressure measurements, demonstrated that central venous pressure was elevated in recumbent crew members even before launch, and that it increased acutely during launch with acceleration loads of up to three times Earth's surface gravity. This increased the weight of the column of blood in the legs "above" the heart and the central venous pressure decreased to below baseline values immediately on reaching orbit. Investigators realized that the dynamics of central blood volume changes were more complex than originally hypothesized.

By measuring and recording arterial blood pressures, heart rate, and rhythm, two-dimensional echocardiography



*In the Spacelab (laboratory in Orbiter payload bay) Astronaut Rhea Seddon, MD, measures cardiac function on Martin Fettman during Columbia life sciences mission STS-58 (1993).*

demonstrated the variety of changes in the cardiovascular system in flight. In-flight heart rate and systolic and diastolic blood pressure decreased when compared to the preflight values. During re-entry into Earth's atmosphere, these values increased past their preflight baseline, reaching maximal values at peak deceleration loading. When crew members stood upright for the first time after landing, both systolic and diastolic pressures significantly decreased from their seated values and the decrease in diastolic pressure was greater in crew members who did not fully inflate their g-suits. Systolic pressure and heart rate returned to preflight values within an hour of landing, whereas all other spaceflight-induced cardiovascular changes were reversed within a week after landing. Furthermore, stress hormones such as adrenaline (involved in the primal "fight or flight response") were increased postflight, whether the astronauts were resting supine or standing.

#### **So, What Does This Mean?**

During weightlessness, there is reduced postural stress on the heart. As expected, the cardiovascular response is muted: blood pressure and heart rate are lower

in the resting astronaut than before flight. The volume of blood ejected from the heart with each beat initially increases because of the headward fluid shift, but it becomes lower than preflight levels after that due to the decreased blood volume.

#### **Cardiac Rhythm Disturbances**

Contrary to popular opinion, shuttle astronauts were not monitored extensively throughout their flights. Electrocardiograms were recorded and transmitted for crew health assurance only on up to two crew members (out of crews numbering up to seven) and only during launch and landing through the 14th shuttle mission, STS-41G (1984). Subsequently, given the established confidence that healthy astronauts could tolerate spaceflight without difficulty, the requirement for even such minimal medical monitoring was eliminated. Later, a purpose-built system for on-board recording of electrocardiograms and blood pressure was used on select volunteer astronauts between 1989 and 1994.

At present, there is little evidence to indicate that cardiovascular changes observed in spaceflight increase



susceptibility to life-threatening disturbances in cardiac rhythms. Certain findings, however, suggest that significant cardiac electrical changes occurred during short and long flights.

NASA systematically studied cardiac rhythm disturbances during some shuttle missions in response to medical reports of abnormal rhythms in nine of 14 spacewalking astronauts between 1983 and 1985. In subsequent studies on 12 astronauts on six shuttle flights, investigators acquired 24-hour continuous Holter recordings of the electrocardiograms during and after altitude chamber training, then again 30 days before launch, during and after each EVA, and after return to Earth. These investigators observed no change in the number of premature contractions per hour during flight compared to preflight or postflight. Given the fact that these data disagreed with other previous reports on astronauts, the investigators recommended that further study was required.

### **Summary**

The Space Shuttle provided many opportunities to study the cardiovascular system due to the high number of flights and crew members, along with an emphasis on life sciences research. This research provided a better understanding of the changes in spaceflight and provided focus for the ISS research program.

## **Nutritional Needs in Space**

### ***Do Astronauts Have Special Nutritional Needs?***

If elite athletes like Olympians have special nutritional needs, do astronauts too? During the shuttle flights, nutrition research indicated that, in general, the answer is no. Research, however, provided the groundwork for long-duration missions, such as for the

ISS and beyond. Additionally, as the expression goes, while good nutrition will not make you an Olympic-quality athlete, inadequate nutrition can ruin an Olympic-quality athlete.

Nutritional needs drive the types and amounts of food available on orbit. Since shuttle flights were short (1 to 2 weeks), nutritional needs were more like those required for a long camping trip. Accordingly, NASA's research focused on the most important nutrients that related to the physiological changes that microgravity induced for such short missions. The nutrients studied were water, energy (calories), sodium, potassium, protein, calcium, vitamin D, and iron.

Many astronauts eat and drink less in flight, probably due to a combination of reduced appetite and thirst, high stress, altered food taste, and busy schedules. Because the success of a flight is based on the primary mission, taking time for eating may be a low priority. Astronauts are healthy adults, so NASA generally uses Earth-based dietary nutrient recommendations; however, researchers commonly found inadequate food intake and corresponding loss of body weight in astronauts. This observation led to research designed to estimate body water and energy needed during spaceflight.

### ***How Much Water Should an Astronaut Consume?***

Water intake is important to prevent dehydration. About 75% of our bodies is water, located mostly in muscles. The fluid in the blood is composed of a noncellular component (plasma) and a cellular component (red blood cells).

NASA measured the various body water compartments using dilution techniques: total body water; extracellular volume (all water not in cells), plasma volume, and blood volume. Because of the lack

of strong gravitational force, a shift of fluid from the lower body to the upper body occurs. This begins on the launch pad, when crew members may lie on their backs for 2 to 3 hours for many flights. Scientists hypothesize that the brain senses this extra upper-level body water and adapts through reduced thirst and, sometimes, increased losses through the kidney—urine. An initial reduction of about 15% water (0.5 kg [1.15 pounds]) occurred in the plasma in flight, thus producing a concentrated blood that is corrected by reducing the levels of red blood cells through a mechanism that reduces new blood cells. Soon after entering space, these two compartments (plasma and red blood cells) return to the same balance as before flight but with about 10% to 15% less total volume in the circulation than before flight. Through unknown mechanisms, extracellular fluid is less and total body water does not change or may decrease slightly, 2% to 3% (maximum loss of 1.8 kg [4 pounds]). From this NASA scientists inferred that the amount of intracellular fluid is increased, although this has not been measured. These major fluid shifts affect thirst and, potentially, water requirements as well as other physiological functions. Water turnover decreases due to a lower amount of water consumed and decreased urine volume—both occur in many astronauts during spaceflight. Since total body water does not change much, recommended water intakes are around 2,000 ml/d (68 oz, or 8.5 cups). Astronauts may consume this as a combination of beverages, food, and water.

Because of potentially reduced thirst and appetite, astronauts must make an effort to consume adequate food and water. Water availability on the shuttle was never an issue, as the potable water was a by-product of the fuel cells. With flights to the Russian space station Mir and the ISS, the ability to



transfer water to these vehicles provided a tremendous help as the space agencies no longer needed to launch water, which is very heavy.

A much-improved understanding of water loss during EVAs occurred during the shuttle period. This information led to the ISS EVA standards. Dehydration may increase body heat, causing dangerously high temperatures. Therefore, adequate water intake is essential during EVAs. NASA determined how much water was needed for long EVAs (6 hours outside the vehicle, with up to 12 hours in the EVA suit). Due to the concern for dehydration, water supplies were 710 to 946 ml (24 to 32 oz, or 3 to 4 cups) in the in-suit drink bag (the only nutrition support available during EVA).

### ***How Spaceflight Affects Kidney Function***

Does the headward fluid shift decrease kidney function? The kidneys depend on blood flow, as it is through plasma that the renal system removes just the right amount of excess water, sodium, metabolic end products like urea and creatinine, as well as other metabolic products from foods and contaminants. So, what is the affect of reduced heart rates and lower blood volumes? Astronauts on several Spacelab flights participated in research to determine any changes in renal function and the hormones that regulate this function. When the body needs to conserve water, such as when sweating or not hydrating enough, a hormone called antidiuretic hormone prevents water loss. Similarly, when the body has too little sodium, primarily due to diet and sweating, aldosterone keeps sodium loss down. All the experiments showed that these mechanisms worked fine in spaceflight. We learned not to worry about the basic functions of the kidney.

### ***Renal Stones***

As stated, the kidney controls excess water. But, what happens if a crew member is dehydrated due to sweating or not consuming enough water? During spaceflight, urine becomes very concentrated with low levels of body water. This concentrated urine is doubly changed by immediately entering microgravity, and the bone starts losing calcium salts. Although these losses were not significant during the short shuttle flights, this urinary increase had the potential to form calcium oxalate renal stones. Furthermore, during spaceflight, protein breakdown increases due to muscle atrophy and some of the end products could also promote renal stones. Due to the potential problem of renal stones, crew members were strongly encouraged to consume more water than their thirst dictated. This work led to the development of countermeasures for ISS crew members.

### ***Sodium and Potassium: Electrolytes Important for Health***

The electrolytes sodium (Na) and potassium (K) are essential components of healthy fluid balance; Na is a primarily extracellular ion while K is a primarily intracellular ion. They are essential for osmotic balance, cell function, and many body chemical reactions. K is required for normal muscle function, including the heart. With changes in fluid balance, what happens to these electrolytes, especially in their relationship to kidney and cardiovascular function?

Total body water levels change with changes in body weight. With weight loss, liver glycogen (polymers of glucose) stores that contain significant associate water are lost, followed by tissue water—fat 14% and lean body mass 75% water. Antidiuretic hormone conserves body water. Aldosterone increases the volume of fluid in the

body and drives blood pressure up, while atrial natriuretic peptide controls body water, Na, K, and fat (adiposity), thereby reducing blood pressure. In the first few days of spaceflight, antidiuretic hormone is high but it then readjusts to controlling body water. Aldosterone and atrial natriuretic peptide reflect Na and water intakes to prevent high blood pressure.

Research from several Spacelab missions demonstrated that in microgravity, astronauts' bodies are able to adjust to the changes induced by microgravity, high Na intakes, and the stress of spaceflight. During spaceflight, Na intakes are generally high while K intakes are low as compared to needs. The astronauts adjust to microgravity within a few days. Although astronauts have less body water and a headward shift of water, these regulatory hormones primarily reflect dietary intakes.

The implications of these data for long-duration flights, such as the ISS, remain unknown. While on Earth, high Na intakes are most often associated with increasing blood pressure. Such intakes also may exacerbate bone loss, which is a problem for astronauts on long-duration spaceflights.

### ***How Many Calories Do Astronauts Need in Spaceflight?***

Because astronauts eat less, research determined the energy level (calories) needed during spaceflight. For selected missions, astronauts completed food records with a bar code reader to obtain good information about dietary intake during spaceflights. These studies showed that most astronauts ate less than their calculated energy needs—on average, about 25% less.

Scientists completed two types of research for measuring astronauts' body energy use. Energy can be



determined from the products of energy metabolism: carbon energy sources like carbohydrates, protein, or fat + oxygen ( $O_2$ ) = heat + carbon dioxide ( $CO_2$ ). We used two methods for shuttle flights. For most flights, all the expired  $CO_2$  was removed by chemical reaction with lithium hydroxide (LiOH) so the amount of  $CO_2$  produced during a flight could be determined.  $CO_2$  that was absorbed into the LiOH could be measured at the end of the flight to determine the energy use by the crew over the entire mission. The second method was to determine the amount of  $CO_2$  and water loss over 3 to 5 days of time per astronaut. Astronauts consumed two stable isotopes (not radioactive), deuterium and  $^{18}O$ , and the levels of these isotopes in urine were measured over a period of several days. The  $O_2$  occurs in the  $CO_2$  and water, but deuterium is only in the water; thus the method allowed for the determination of the  $CO_2$  produced by an astronaut. Surprisingly for both methods, the levels of energy used were the same in flight as on Earth. As a result of this research, NASA dietitians use gender and weight, along with allowing for moderate activity values, to calculate astronauts' energy needs for spaceflight. This method has worked for many years to ensure adequate provision of space foods.

One of the major contributions of EVA research is the increased ability to predict energy expenditure during spacewalks. EVAs were routinely conducted from the shuttle. Energy expenditure was important for both suit design and dietary intakes before and after a spacewalk. After conducting thousands of EVA hours, NASA knows that the energy expenditure was not high for a short period of time, similar to walking 4 to 6.4 kph (2.5 to 4.0 mph). Nearly all EVAs lasted around 6 hours, however, and

thus energy expenditure added up to a fairly high level. The lower energy levels occurred when crew members were within the payload bay, primarily doing less-demanding work for short periods. With the construction of the ISS, EVA activity increased along with duration to about 4 to 8 kJ/hr (250 to 500 kcal/hr). For an 8-hour EVA, this was significant. Of course, as previously described, increased energy expenditure increased water needs.

### ***Protein and Amino Acids: Essential for Maintenance of Muscle Function***

Protein and its components (amino acids) are essential for all body chemical reactions, structure, and muscles. In spaceflight, total body protein turnover increases as measured by the loss of the orally ingested stable isotope  $^{15}N$ -glycine, which was measured in body tissues such as saliva and blood. Glycine is an amino acid that occurs abundantly in proteins, so changes in blood levels indicate the amount of glycine moved to the tissues for protein syntheses. Some of the increased turnover may be due to the catabolic state of weight loss found with many astronauts due to lower-than-needed energy intakes. There is evidence, even with short-term shuttle flights, that skeletal muscle function decreases. The mild stress of spaceflight found with hard-working astronauts may increase protein breakdown. Increased stress was determined by increased levels of blood and urinary cortisol. Dietary protein levels are already high in spaceflight. Protein recommendations are the same as ground-based dietary guidelines.

### ***Bones Need Calcium and Vitamin D***

Studies with Skylab astronauts in the 1970s and shuttle crew members found calcium (Ca) losses increased during flight, probably through removal from

bone. NASA confirmed this initial observation of bone loss in the 1990s by using the latest biological markers technology. In fact, research showed that as soon as the astronauts arrived in space, they started losing bone.

Vitamin D is essential for the body to absorb the dietary Ca that is used for bone and other tissue functions. Vitamin D syntheses occur in the skin during exposure to sunlight. In spacecraft, however, sunlight is not tolerated: the rays are too strong because flights take place above the protective atmosphere. Studies completed during the Shuttle-Mir and European Space Agency research programs showed low vitamin D levels could be a problem for Ca absorption and good bone health. A vitamin D supplement is provided for ISS long-duration spaceflights.

### ***Too Much Iron May Be Toxic***

Changes in astronaut's red blood cells and iron (Fe) levels are similar to those of a person who lives at a high altitude (e.g., 3,658 m [12,000 ft]) coming to sea level. Both have too much available Fe (i.e., not bound up in red blood cells).

Fe is an important part of red blood cells that brings oxygen from the lungs to the tissues. Low levels of red blood cells cause fatigue. The initial decrease in plasma volume produces an increased concentration of red blood cells. The body may then perceive too many red blood cells and make adjustments accordingly. A 12% to 14% decrease in the number of red blood cells occurs within a couple of weeks of spaceflight. To maintain the correct percent of red blood cells (about 37% to 51% of the blood), newly formed red blood cells are destroyed until a new equilibrium is achieved. The red blood cell Fe is released back into the



blood and tissues, and no mechanism except bleeding can reduce the level of body Fe. Excess Fe could potentially have toxic effects, including tissue oxidation and cardiovascular diseases. Shuttle research showed that the dietary Fe need is below that needed on Earth because of the reduced need for red blood cell production.

**Summary of Nutritional Needs Found for Space Shuttle Astronauts**

Nutrient	Level
Energy men 70 kg (~154 pounds)	12.147 MJ/d (2,874 kcal/d)
Energy women 60 kg (~132 pounds)	9.120 MJ/d (2,160 kcal/d)
Protein	12% to 15% of energy intake < 85 g/d
Water	2,000 ml/d
Na	1,500 to 3,500 mg/d
K	3,500 mg/d
Fe	10 mg/d
Vitamin D	10 ug/d
Calcium	800 to 1,200 mg

**Changes in Immunity and Risk of Infectious Disease During Spaceflight**

Humans are healthy most of the time, despite being surrounded by potentially infectious bacteria, fungi, viruses, and parasites. How can that be? The answer is the immune system. This highly complex and evolved system is our guardian against infectious diseases and many cancers. It is essential that astronauts have a robust, fully functional immune system just as it is for us on Earth. Astronauts are very healthy, exquisitely conditioned, and well nourished—all factors promoting healthy immunity. In addition, exposures to potential microbial

pathogens are limited by a series of controls. All shuttle consumables (e.g., drinking water and food) and environment (breathing air and surfaces) are carefully examined to ensure the health and safety of the astronauts. Preflight restrictions are in place to limit exposure of astronauts to ill individuals. This system works very well to keep astronauts healthy before, during, and after spaceflight. Since spaceflight is thought to adversely affect the immune system and increase disease potential of microorganisms, the shuttle served as a platform to study immunity and microbes’ ability to cause disease.

**The Immune System**

Your immune system quietly works for you, a silent army within your body protecting you from microorganisms that can make you sick. If it is working well, you never know it. But, when it’s not working well, you will probably feel it.

The human immune system consists of many distinct types of white blood cells residing in the blood, lymph nodes, and various body tissues. The white blood cells of the immune system function in a coordinated fashion to protect the host from invading pathogens (bacteria, fungi, viruses, and parasites).

There are various elements of immunity. Innate immunity is the first line of defense, providing nonspecific killing of microbes. The initial inflammation associated with a skin infection at a wound site is an example of innate immunity, which is primarily mediated by neutrophils, monocytes, and macrophages. Cell-mediated immunity provides a specific response to a particular pathogen, resulting in immunologic “memory” after which immunity to that unique pathogen is conferred. This is the part of the immune system that forms the basis of

how vaccines work. T cells are part of cell-mediated immunity, while B cells provide the humoral immune response. Humoral immunity is mediated by soluble antibodies—highly specific antimicrobial proteins that help eliminate certain types of pathogens and persist in the blood to guard against future infections. Upon initial exposure to a unique pathogen such as a herpes virus, the number of specific types of T and B cells expands in an attempt to eliminate the infection. Afterward, smaller numbers of memory cells continue to patrol the body, ever vigilant for another challenge by that particular pathogen. An immune response can be too strong at times, leading to self-caused illness without a pathogen. Examples of this are allergies and autoimmune diseases. At other times an immune response is not strong enough to fight an infection (immunodeficiency). Acquired Immunodeficiency Syndrome (AIDS) and cancer chemotherapy are both examples of immunodeficiency conditions caused by the loss of one or more types of immune cells.

**Spaceflight-associated Changes in Immune Regulation**

Changes in regulation of the immune system are found with both short- and long-duration spaceflight. Studies demonstrated that reduced cell mediated immunity and increased reactivation of latent herpes viruses occur during flight. In contrast, humoral (antibody) immunity was found to be normal when astronauts were immunized during spaceflight. Other shuttle studies showed reduced numbers of T cells and natural killer cells (a type of white blood cell important for fighting cancer and virally infected cells), altered distribution of the circulating leukocyte (white blood cell) subsets, altered stress hormone levels, and altered cytokine



levels. Reduced antimicrobial functions of monocytes, neutrophils, and natural killer cells also occur when measured soon after spaceflight. Cytokines are small proteins produced by immune cells; they serve as molecular messengers that control the functions of specialized immune cells. Cytokines are released during infection and serve to shape the immune response. There are many cytokines, and they can be grouped in several ways. Th1 cytokines are produced by specialized T cells to promote cell-mediated immunity, whereas Th2 cytokines promote

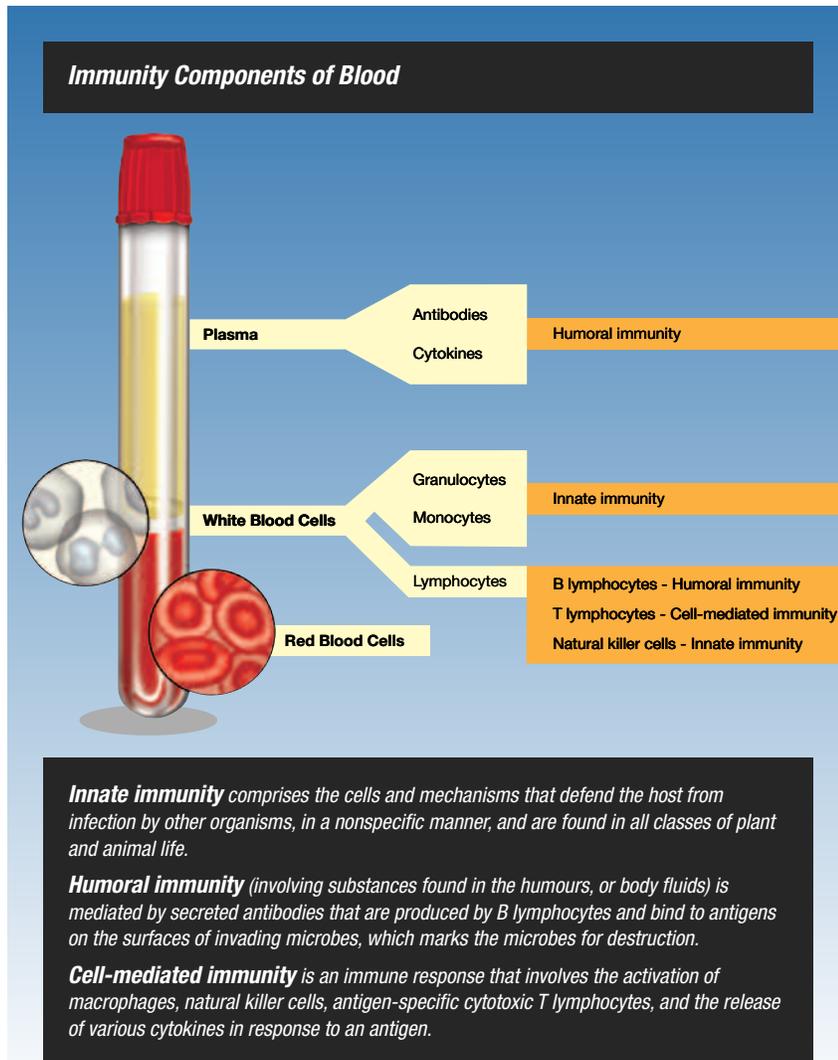
humoral immunity. One hypothesis to explain immune dysregulation during spaceflight is a shift in the release of cytokines from Th1 toward Th2 cytokines. Data gained from the shuttle research support this theory.

### **Selected Space Shuttle Immune Studies**

#### **Hypersensitivity**

Hypersensitivity occurs when the immune response to a common antigen is much stronger than normal. Usually, this manifests itself as a rash and is

commonly measured via skin testing. Briefly, seven common antigens, bacteria, *Proteus* (common in urinary track infections), *Streptococcus*, tuberculin and *Trichophyton* (skin diseases), and yeast, *Candida* (known to increase in the immune compromised), are injected into the forearm skin. For most normal individuals, the cell-mediated arm of the immune system reacts to these antigens within 2 days, resulting in a visible red, raised area at the site of the injections. These reactions are expected and represent a healthy immune response. The red, raised circular area for each antigen can be quantified. To test astronauts, antigens were injected 46 hours before landing, and the evaluation of the reaction took place 2 hours after landing. Data showed that, as compared to preflight baseline testing, the cell-mediated immunity was significantly reduced during flight. Both the number of reactions and the individual reaction size were reduced during flight. These data indicated for the first time that immunity was reduced during short-duration spaceflight. Any associated clinical risks were unknown at the time. The possibility that this phenomenon would persist for long-duration flight was also unknown. Similar reductions in cell-mediated immunity were reported in Russian cosmonauts during longer missions.



#### **Studies of the Peripheral Mononuclear Cells**

Peripheral mononuclear cells are blood immune cells. Their numbers are a measure of the current immune status of a subject. During the latter stages of the 11-day STS-71 (1995) shuttle mission, the shuttle astronauts and the returning long-duration astronauts (from Mir space station) stained samples of their peripheral



## Herpes Viruses Become Active During Spaceflight

Herpes viruses, the most commonly recognized latent viruses in humans, cause specific primary diseases (e.g., chicken pox), but may remain inactive in nervous tissue for decades. When immune response is diminished by stress or aging, latent viruses reactivate and cause disease (e.g., shingles).

Epstein-Barr virus reactivated and appeared in astronauts' saliva in large numbers during spaceflight. Saliva collected during the flight phase contained tenfold more virus than saliva collected before or after flight. This finding correlated with decreased

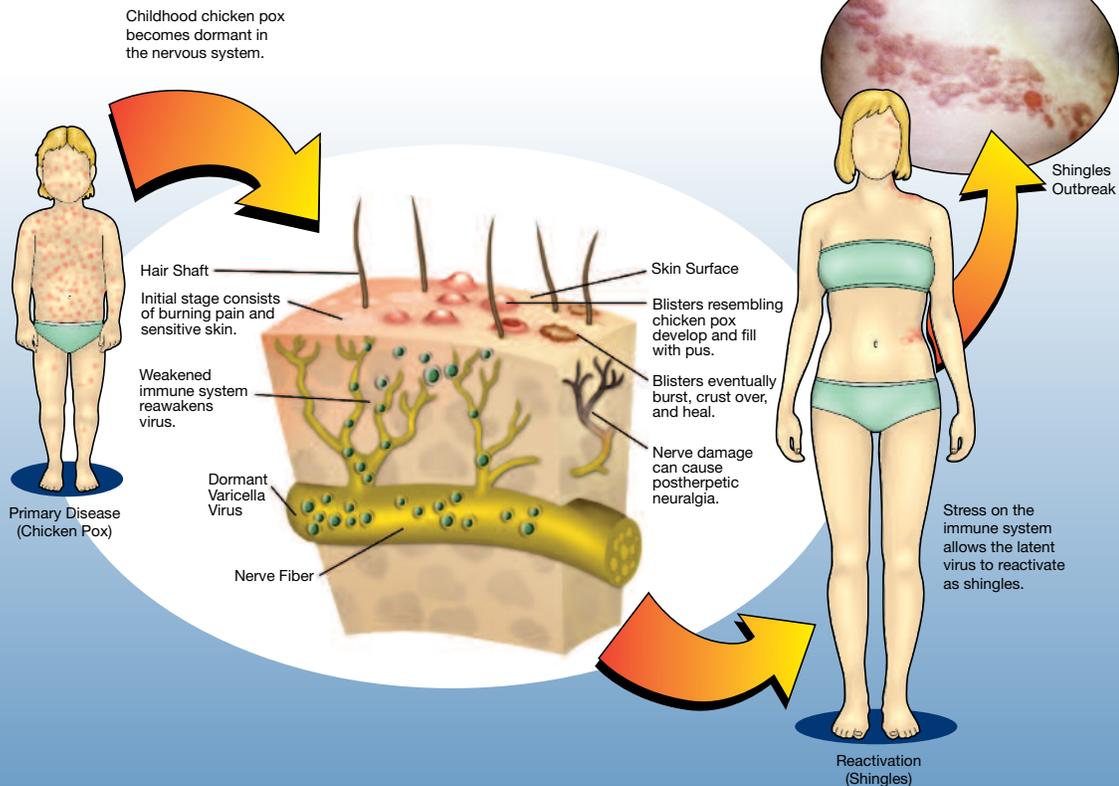
immunity in astronauts during flight. The causes of reduced immunity are unknown, but stress associated with spaceflight appears to play a prominent role, as the levels of stress hormones increase during spaceflight. The resulting decreased immunity allows the viruses to multiply and appear in saliva. The mechanism for Epstein-Barr virus reactivation seems to be a reduction in the number of virus-specific T cells leading to decreased ability to keep Epstein-Barr virus inactive.

Cytomegalovirus, another latent virus, also reactivated and appeared in astronaut

urine in response to spaceflight. Healthy individuals rarely shed cytomegalovirus in urine, but the virus is commonly found in those with compromised immunity.

Scientists also studied Varicella-Zoster virus, the causative agent of chicken pox and shingles. These astronaut studies were the first reports of the presence of this infectious virus in saliva of asymptomatic individuals. A rapid, sensitive test for use in doctors' offices to diagnose shingles and facilitate early antiviral therapy resulting in reductions in nerve damage was a product of this study.

### Role of Varicella-Zoster Virus in Chicken Pox and Shingles





blood immune cells with various dyes using unique and patented equipment developed at Johnson Space Center. These data showed that the major “bulk” levels of peripheral blood immune cells did not appear to be altered during flight.

### Summary

The laboratory capabilities of the Space Shuttle allowed our first systematic assessment of the effects of space travel on the human immune system. Most indicators of immunity were altered during short-duration spaceflight, which is a uniquely stressful environment. These stressors were likely major contributors to the observed changes in immunity and the increased viral reactivation. Latent viruses were shown to be sensitive indicators of immune status. Bacterial pathogens were also shown to be more virulent during spaceflight. It is unknown whether these are transient effects or whether they will persist for long-duration missions. These important data will allow flight surgeons to determine the clinical risk for exploration-class space missions (moon, Mars) related to immunology, and to further the development of countermeasures for those risks. These studies and the hardware developed to support them serve as the platform from which new studies on board the ISS were initiated. It is expected that the ISS studies will allow a comprehensive assessment of immunity, stress, latent viral reactivation, and bacterial virulence during long-duration spaceflight.

## Habitability and Environmental Health

### Habitability

The shuttle contributed significantly to advances in technologies and processes to improve the habitability of space vehicles and enable humans to live and work productively in space. These shuttle-sponsored advances played a key role in our coming to view living and working in space as not only possible but also achievable on a long-term basis.

Habitability can be defined as the degree to which an environment meets an individual’s basic physiological and psychological needs. It is affected by multiple factors, including the size of the environment relative to the number of people living and working there and the activities to be undertaken. Other habitability factors include air, water, and food quality as well as how well the environment is designed

and equipped to facilitate the work that is to be done.

Resource limitations conspire to severely limit the habitability of space vehicles. Spacecraft usually provide minimal volume in which crew members can live and work due to the high cost of launching mass into space. The spacecraft’s environmental control system is usually closed to some degree, meaning that spacecraft air and water are recycled and their quality must be carefully maintained and monitored. It may be several months between when food is prepared and when it is consumed by a space crew. There is normally a limited fresh resupply of foods. Care must be taken to assure the quality of the food before it is consumed.

The following sections illustrate some of the technologies and processes that contributed to the habitability of the shuttle and provided a legacy that will help make it possible for humans to live safely and work productively in space.



*On STS-90 (1998), three Space Shuttle Columbia crew members—Astronauts James Pawelczyk, Richard Searfoss, and Richard Linnehan—meet on the middeck, where the crew ate, slept, performed science, prepared for extravehicular activities (spacewalks), exercised, took care of personal hygiene needs, and relaxed.*



## Innovations Improve Habitability

### Restraints and Mobility Aids

One of the most successful aids developed through the program, and one that will be used on future spacecraft, to support crew member physical stability in microgravity is foot restraints. It is nearly impossible to accomplish tasks in microgravity without stabilizing one's feet. NASA scientists developed several designs to make use of the body's natural position while in space. One design has foot loops and two-point leg/foot restraints used while a crew member works at a glove box. These restraints stabilize a crew member. The effectiveness of a restraint system relates to the simplicity of design, comfort, ease of use, adjustability, stability, durability, and flexibility for the range of the task. Other restraint systems developed include handrails, bungee cords, Velcro®, and flexible brackets. Furthermore, foot restraints aid in meeting other challenges such as limited

visibility and access to the activity area. The latter difficulties can lead to prolonged periods of unnatural postures that may potentially harm muscles or exacerbate neurological difficulties.

### Cursor Control Devices

The shuttle spacecraft environment included factors such as complex lighting scenarios, limited habitable volume, and microgravity that could render Earth-based interface designs less than optimal for space applications. Research in space human factors included investigating ways to optimize interfaces between crew members and spacecraft hardware, and the shuttle proved to be an excellent test bed for evaluating those interfaces.

For example, while computer use is quite commonplace today, little was known about how, or if, typical cursor control devices used on Earth would work in space. NASA researchers conducted a series of experiments to gather information about the desirable



Example of a cursor control device with a trackball as used with ungloved and gloved hands.

and undesirable characteristics of cursor control devices using high-fidelity environments. Experiments began in ground laboratories and then moved to the KC-135 aircraft for evaluation in a short-duration microgravity environment during parabolic flight. The experiments culminated with flight experiments on board Space Transportation System (STS)-29 (1989), STS-41 (1990), and STS-43 (1991). These evaluations and experiments used on-board crew members to take the devices through the prescribed series of tasks.

## Anchoring Improves Performance



### Without Constraints

On STS-73 (1995) Astronaut Kathryn Thornton works at the Drop Physics Module on board the Spacelab science module located in the cargo bay of the Earth-orbiting shuttle. Notice that Dr. Thornton is anchoring her body by using a handrail for her feet and right hand. This leaves only one free hand to accomplish her tasks at that workstation and would be an uncomfortable position to hold for a long period of time.

### With Constraints

Also on STS-73, Astronaut Catherine Coleman uses the advanced lower body extremities restraint at the Spacelab glove box. With Dr. Coleman's feet and knees anchored for body stability, she has both hands free to work for longer periods, providing her stability and comfort.





It cannot be assumed that computer equipment, like cursor control devices (e.g., a trackball, an optical mouse), used on Earth will behave the same way in space. Not only does microgravity make items “float,” in general the equipment might be used while a crew member is wearing gloves—and the gloves could be pressurized at the time. For example, a trackball has a certain amount of movement allowed within its casing. In space, the ball will float, making it much more difficult to use the trackball and be accurate. During STS-43, the shuttle crew worked with a trackball that was modified to reduce the “play,” and they reported that the mechanism worked well. This modification resulted in the fastest and most accurate responses.

Those tests in the flight environment paved the way for the types of equipment chosen for the International Space Station (ISS). The goal was to provide the best equipment to ensure quick and precise execution of tasks by crew members. As computer technology advances, NASA will continue investigations involving computer hardware as spacecraft and habitats are developed.

### ***Shuttle Food System Legacy***

Does NASA have a grocery store in space? The answer is no. One significant change NASA made to the space food system during the Space Shuttle Program, however, was the addition of a unique bar code on each food package to facilitate on-orbit science.

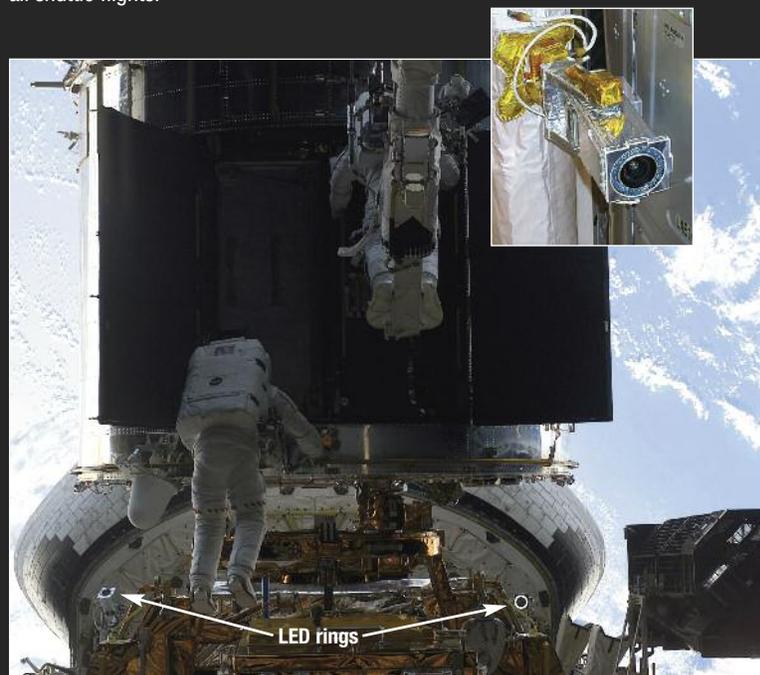
When crew members began participating in experiments on orbit that required them to track their food consumption, a method was needed that would promote accurate data collection while minimizing crew time; thus, the

## **White Light-emitting Diode Illuminators**

As the shuttle orbited Earth, the crew experienced a sunrise and sunset every 45 minutes on average. This produced dramatic changes in lighting conditions, making artificial light sources very important for working in space.

Because of power and packaging constraints during the Space Shuttle Program, most artificial lights were restricted to fixed locations. With the assembly of the International Space Station and the maintenance of the Hubble Space Telescope, NASA felt it would be a great improvement to have lights mounted on all of the shuttle cameras. These light sources had to be durable, lightweight, and low in power requirements—the characteristics of light-emitting diodes (LEDs).

In 1995, NASA began using white LED lights for general illumination in camera systems several years in advance of industry. These early lights were designed as rings mounted around the lens of each camera. The four payload bay cameras were equipped with four LED light systems capable of being pointed with the pan-and-tilt unit of each camera. NASA also outfitted the two robotic arm cameras with LED rings. In June 1998, the first white 40 LED illumination system was flown. In May 1999, white 180 LED illuminators were flown. These lighting systems remained in use on all shuttle flights.



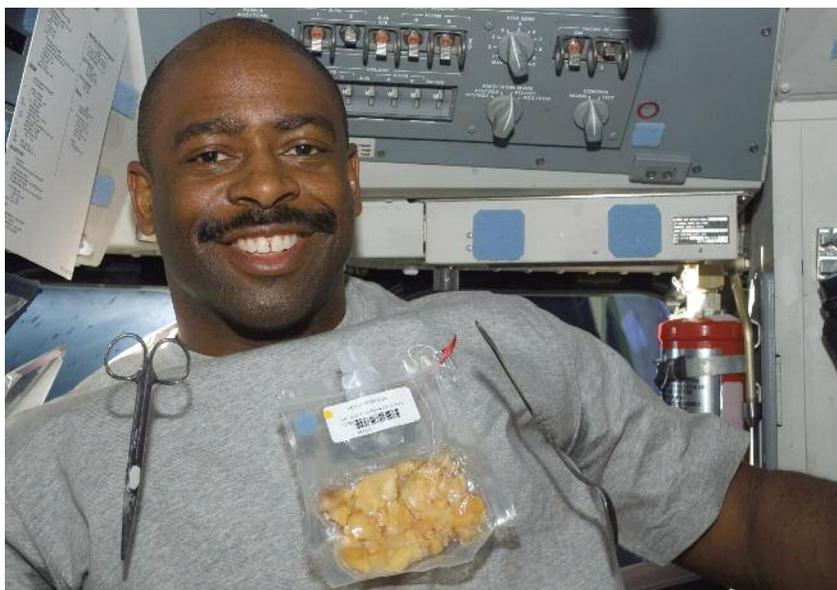
*Light-emitting diode (LED) rings mounted on the two shuttle cameras in the aft payload bay of shuttle.*



bar code. Crew members simply used a handheld scanning device to scan empty food packages after meals. The device automatically recorded meal composition and time of consumption. Not only did bar codes facilitate science, they also had the additional benefit of supporting the Hazard Analysis and Critical Control Point program for space food.

Hazard Analysis and Critical Control Point is a food safety program developed for NASA's early space food system. Having a unique bar code on each food package made it easy to scan the food packages as they were stowed into the food containers prior to launch. The unique bar code could be traced to a specific lot of food. This served as a critical control point in the event of a problem with a food product. If a problem had arisen, the bar code data collected during the scanning could have been used to locate every package of food from that same lot, making traceability much easier and more reliable. This system of bar coding food items carried over into the ISS food system.

Food preparation equipment also evolved during the shuttle era. The earliest shuttles flew with a portable water dispenser and a suitcase-sized food warmer. The first version of the portable water dispenser did not measure, heat, or chill water, but it did allow the crew to inject water into foods and beverages that required it. This dispenser was eventually replaced by a galley that, in addition to measuring and injecting water, chilled and heated it as well. The shuttle galley also included an oven for warming foods to serving temperature. Ironically, the food preparation system in use on the ISS does not include chilled water and, once again, involves the



*On STS-122 (2007), Astronaut Leland Melvin enjoys his dessert of rehydrated peach ambrosia. Also shown is the pair of scissors that is needed to open the pouch. On the pouch is a bar code that is used to track the food. The blue Velcro® allows the food to be attached to the walls.*

use of the suitcase-sized food warmer for heating US food products.

Food packaging for shuttle foods also changed during the course of the program. The original rigid, rectangular plastic containers for rehydratable foods and beverages were replaced by flexible packages that took up less room in storage and in the trash. The increase in crew size and mission duration that occurred during the program necessitated this change. These improvements continue to benefit the ISS food system.

## **Environmental**

### ***Environmental Conditions***

#### ***Maintaining a Healthy Environment During Spaceflight***

The shuttle crew compartment felt like an air-conditioned room to astronauts living and working in space, and the Environmental Control and Life Support System created that habitable

environment. In fact, this system consisted of a network of systems that interacted to create such an environment, in addition to cooling or heating various Orbiter systems or components. The network included air revitalization, water coolant loop, active thermal control, atmosphere revitalization pressure control, management of supply and wastewater, and waste collection.

The Air Revitalization System assured the safety of the air supply by using lithium hydroxide to maintain carbon dioxide (CO<sub>2</sub>) and carbon monoxide at nontoxic levels. It also removed odors and trace contaminants through active charcoal, provided ventilation in the crew compartment via a network of fans and ducting, controlled the cabin's relative humidity (30% to 75%) and temperature (18°C [65°F] to 27°C [80°F]) through cabin heat exchangers for additional comfort, and supplied air cooling to various flight deck and middeck electronic avionics as well as the crew compartment.



The water coolant loop system collected heat from the crew compartment cabin heat exchanger and from some electronic units within the crew compartment. The system transferred the excess heat to the water coolant/Freon<sup>®</sup>-21 coolant loop heat exchanger of the Active Thermal Control System, which then moved excess heat from the various Orbiter systems to the system heat sinks using Freon<sup>®</sup>-21 as a coolant.

During ground operations, the ground support equipment heat exchanger in the Orbiter's Freon<sup>®</sup>-21 coolant loops rejected excess heat from the Orbiter through ground systems cooling. Shortly after liftoff, the flash evaporator (vaporization under reduced pressure) was activated and provided Orbiter heat rejection of the Freon<sup>®</sup>-21 coolant loops through water boiling. When the Orbiter was on orbit and the payload bay doors were opened, radiator panels on the underside of the doors were exposed to space and provided heat rejection. If combinations of heat loads and the Orbiter attitude exceeded the capacity of the radiator panels during on-orbit operations, the flash evaporator was activated to meet the heat rejection requirements. At the end of orbital operations, through deorbit and re-entry, the flash evaporator was again brought into operation until atmospheric pressure, about 30,480 m (100,000 ft) and below, no longer permitted the flash evaporation process to provide adequate cooling. At that point, the ammonia boilers rejected heat from the Freon<sup>®</sup>-21 coolant loops by evaporating ammonia through the remainder of re-entry, landing, and postlanding until ground cooling was connected to the ground support equipment heat exchanger.

Atmosphere revitalization pressure control kept cabin pressure around

sea-level pressure, with an average mixture of 80% nitrogen and 20% oxygen. Oxygen partial pressure was maintained between 20.3 kPa (2.95 pounds per square inch, absolute [psia]) and 23.8 kPa (3.45 psia), with sufficient nitrogen pressure of 79.3 kPa (11.5 psia) added to achieve the cabin total pressure of 101.3 kPa (14.7 psia) +/-1.38 kPa (0.2 psia). The Pressure Control System received oxygen from two power reactant storage and distribution cryogenic oxygen systems in the mid-fuselage of the Orbiter. Nitrogen tanks, located in the mid-fuselage of the Orbiter, supplied gaseous nitrogen—a system that was also used to pressurize the potable and wastewater tanks located below the crew compartment middeck floor.

Three fuel-cell power plants produced the astronauts' potable water, to which iodine was added to prevent bacterial growth, that was stored in water tanks. Iodine functions like the chlorine that is added to municipal water supplies, but it is less volatile and more stable than chlorine. Condensate water and human wastewater were collected into a wastewater tank, while solid waste remained in the Waste Collection System until the Orbiter was serviced during ground turnaround operations.

#### ***Space Shuttle Environmental Standards***

We live on a planet plagued with air and water pollution problems because of the widespread use of chemicals for energy production, manufacturing, agriculture, and transportation. To protect human health and perhaps the entire planet, governmental agencies set standards to control the amount of potentially harmful chemicals that can be released into air and water and then monitor the results to show compliance with standards. Likewise,

on the shuttle, overheated electronics, systems leaks, propellants, payload chemicals, and chemical leaching posed a risk to air and water quality. Standards were necessary to define safe air and water, along with monitoring systems to demonstrate a safe environment.

#### **Air**

Both standards and methods as well as instruments to measure air quality were needed to ensure air quality. For the shuttle, NASA had a formalized process for setting spacecraft maximum allowable concentrations. Environmental standards for astronauts must consider the physiological effects of spaceflight, the continuous nature of airborne exposures, the aversion to drinking water with poor aesthetic properties, and the reality that astronauts could not easily leave a vehicle if it were to become dangerously polluted.

On Earth, plants remove CO<sub>2</sub>—a gas exhaled in large quantities as a result of human metabolism—from the atmosphere. By contrast, CO<sub>2</sub> is one of the most difficult compounds to deal with in spaceflight. For example, accumulation of CO<sub>2</sub> was a critical problem during the ill-fated Apollo 13 return flight. As the disabled spacecraft returned to Earth, the crew had to implement unanticipated procedures to manage CO<sub>2</sub>. This involved duct-taping filters and tubing together to maintain CO<sub>2</sub> at tolerable levels. Such extreme measures were not necessary aboard shuttle; however, if the crew forgot to change out filters, the CO<sub>2</sub> levels could have exceeded exposure standards within a few hours.

Although older limits for CO<sub>2</sub> were set at 1%, during NASA's new standard-setting process with the National Research Council it became



## Combustion Product Analyzer Ensured Crew Breathed Clean Air After Small Fire in Russian Space Station

The combustion product analyzer flew on every Space Shuttle flight from 1990 through 1999 and proved its value during the Shuttle-Mir Program (1995-1998). On the seventh joint mission in 1998, no harm seemed to have occurred during an inadvertent valve switch on an air-purifying scrubber. In fact, during this time, the crew—including American Andrew Thomas—participated in a video presentation transmitted back to Earth; however, shortly after the valve switch, the crew experienced headaches. As on Earth, when occupants of a house or building experience headaches simultaneously, it can indicate that the air has been severely degraded. The crew followed procedures and activated the combustion product analyzer, designed to detect carbon monoxide (CO), hydrogen cyanide, hydrogen chloride, and hydrogen fluoride. The air contained over 500 parts per million of CO, significantly above acceptable concentrations. This high concentration was produced by hot air flowing through a paper filter and charcoal bed and then into the cabin when the valve was mistakenly switched on. The combustion product analyzer was used to follow the cleanup of the CO. Archival samples confirmed the accuracy of the analyzer's results. The success of this analyzer and its successor—the compound specific analyzer-combustion products—led to the inclusion of four units (compound specific analyzer-combustion products) on the International Space Station and a combustion products analyzer on future crew exploration vehicles.



*Commander Robert Gibson and Astronaut Jan Davis check the combustion product analyzer during STS-47 (1992).*

clear that 1% was too high and, therefore, the spacecraft maximum allowable concentration was reduced to 0.7%. Even this lower value proved to be marginal under some conditions. For example, the shuttle vehicle did not have the capability to measure local pockets of CO<sub>2</sub>, and those pockets could contain somewhat higher levels than were found in the general air. That was especially true in the absence of gravity where convection was not available to carry warm, exhaled air upward from the astronaut's breathing zone. Use of a light-blocking curtain during a flight caused the crew to experience headaches on awakening, and this was attributed to accumulation of CO<sub>2</sub> because the crew slept in a confined space and the curtain obstructed normal airflow.

Setting air quality standards for astronaut exposures to toxic compounds is not a precise science and is complicated. NASA partnered with the National Research Council Committee on Toxicology in 1989 to set and rigorously document air quality standards for astronauts during shuttle spaceflight.

The spaceflight environment is like Earth in that exposure standards can control activities when environmental monitors suggest the need for control. For example, youth outdoor sports activities are curtailed when ozone levels exceed certain standards on Earth. Likewise, spacecraft maximum allowable concentrations for carbon monoxide, a toxic product of combustion, were used to determine criteria for the use of protective masks in the event of an electrical burn. The shuttle Flight Rules provided the criteria. Ranges for environmental monitoring instruments were also based on spacecraft maximum allowable



## Measuring Airborne Volatile Organic Compounds

Volatile organic compounds are airborne contaminants that pose a problem in semi-closed systems such as office buildings with contributions from carpets, furniture, and paper products as well as in closed systems such as airplanes and spacecraft. These contaminants cause headaches, eye and skin irritation, dizziness, and even cancer.

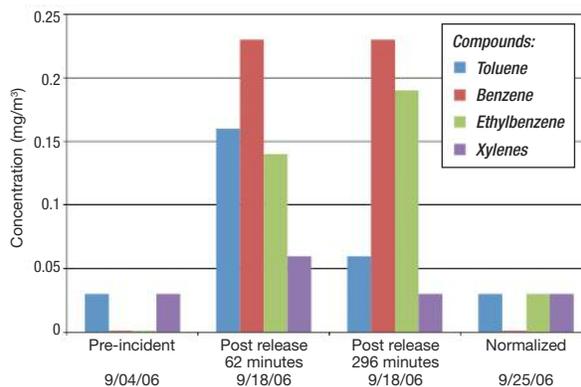
NASA needed to be able to measure such compounds for the International Space Station (ISS), a long-term closed living situation. Therefore, in the latter 1990s, the shuttle was used as a test bed for instruments considered for use on the ISS.

Shuttle flights provided the opportunity to assess the performance of a volatile organic analyzer-risk mitigation experiment in microgravity on STS-81 (1997) and STS-89 (1998). Results confirmed component function and improved the instrument built for ISS air monitoring.

The volatile organic analyzer operated episodically on ISS since 2001 and provided timely and valuable information during the Elektron (Russian oxygen generation system) incident in September 2006 when the crew tried to restart the Elektron and saw what appeared to be smoke emanating from the device. The volatile organic analyzer collected and analyzed samples prior to the event and during cleanup. Data showed that the event had started before the crew noticed the smoke, but the concentrations of the contaminants released were not a health hazard.



**Contaminants: Elektron Incident on the Russian Space Station Mir**



*This chart plots the course of the Elektron incident showing the concentrations of toluene, benzene, ethylbenzene, and xylenes—all serious toxins—released into the air. In 2004, the levels of the four contaminants were very low, as measured by the volatile organic analyzer and grab samples returned to Earth for analysis. During the incident, the analyzer measured increases in the four compounds. Grab samples confirmed the higher levels for these compounds and verified that the analyzer had worked. The next available data showed the contaminants had returned to very low levels.*

*During the STS-89 shuttle dock with Russian space station Mir, Astronaut Bonnie Dunbar goes through her checklist to start the volatile organic analyzer sample acquisition sequence.*



concentrations. For example, the monitoring requirements for hydrogen cyanide, another toxic combustion product, were based on spacecraft maximum allowable concentrations to determine how sensitive the monitor must be. By analogy with Earth-based environmental monitoring, spaceflight monitors needed the ability to indicate when safe conditions had returned so that normal operations could resume.

### ***Water***

NASA recognized the need for unique water-quality standards. Although the effort to set specific water-quality standards, called spacecraft water exposure guidelines, did not begin until 2000, NASA quickly realized the value of these new limits. One of the first spacecraft water-exposure guidelines set was for nickel, a slightly toxic metal often found in water that has been held in metal containers for some time. The primary toxic effect of concern was nickel's adverse effect on the immune system. High nickel levels had been observed from time to time in the shuttle water system based on the existing requirements in NASA documents. This sometimes caused expensive and schedule-breaking activity at Kennedy Space Center to deal with these events. When National Research Council experts accepted a new, higher standard, the old standard was no longer applied to shuttle water and the nickel "problem" became history.

### ***Toxicants From Combustion***

Fire is always a concern in any environment, and a flame is sometimes difficult to detect. First responders must have instruments to quickly assess the contaminants in the air on

arriving at the scene of a chemical spill, fire, or building where occupants have been overcome by noxious fumes. Additionally, these instruments must be capable of determining when the cleanup efforts have made it safe for unprotected people to return. When a spill, thermodegradation, or unusual odor occurs on a spacecraft, crew members are the first responders. They need the tools to assess the situation and track the progress of the cleanup. As a result of shuttle experiments, NASA was able to provide crews with novel instruments to manage degradations in air quality caused by unexpected events.

The combustion products analyzer addressed spacecraft thermodegradations events, which can range from overheated wiring to a full-fledged fire. Fire in a sealed, remote capsule is a frightening event. A small event—overheated wire (odor produced)—occurred on STS-6 (1983), but it wasn't until 1988, when technology advances improved the reliability and shrank the size of monitors, that a search for a combustion products analyzer was initiated. Before the final development of the analyzer, however, a more significant event occurred on STS-28 (1989) that hastened the completion of the instrument. On STS-28, a small portion of teleprinter cable pyrolyzed and the released contaminants could have imperiled the crew if more of the cable had burned. The combustion products analyzer requirements were to measure key contaminants in the air following thermodegradation incidents, track the effectiveness of cleanup efforts, and determine when it was safe to remove protective gear.

Toxic containments may be released from burning materials depending on the type of materials and level of oxygen. For spaceflight, NASA identified five marker compounds: carbon monoxide (odorless and colorless gas) released from most thermodegradation events; hydrogen chloride released from polyvinyl chloride; hydrogen fluoride and carbonyl fluoride associated with Teflon®; and hydrogen cyanide released from Kapton®-coated wire and polyurethane foam. The concentration range monitored for each marker compound was based on the established spacecraft maximum allowable concentrations at the low end and, at the other end of the range, an estimated highest concentration that might be released in a fire.

An upgraded combustion product analyzer is now used on the ISS, demonstrating that the technology and research on fire produced methods that detect toxic materials. The results indicate when it is safe for the astronauts to remove their protective gear.

## **Safeguarding the Astronauts From Microorganisms—Prevention of Viral, Bacterial, and Fungal Diseases**

Certain bacteria, fungi, and viruses cause acute diseases such as upper respiratory problems, lung diseases, and gastrointestinal disease as well as chronic problems such as some cancers and serious liver problems. In space, astronauts are exposed to microorganisms and their by-products from the food, water (both used for food and beverage rehydration,



and for personal hygiene), air, interior surfaces, and scientific investigations that include animals and microorganisms. The largest threat to the crew members, however, is contact with their crewmates.

The shuttle provided an opportunity to better understand the changes in microbiological contamination because, unlike previous US spacecraft for human exploration, the shuttle was designed to be used over many years with limited refurbishment between missions. Risks associated with the long-term accumulation of microorganisms in a crewed compartment were unknown at the start of the shuttle flights; however, many years of studying these

microorganisms produced changes that would prevent problems for the ISS and the next generation of crewed vehicles. With assistance from industry and government standards (e.g., Environmental Protection Agency) and expert panels, NASA established acceptability limits for bacteria and fungi in the environment (air and surfaces) and consumables (food and water). Preflight monitoring for spaceflight was thorough and included the crew, spaceflight food, potable water, and vehicle air and surfaces to ensure compliance with these acceptability standards. NASA reviewed all flight payloads for biohazardous materials. Space Shuttle acceptability limits evolved with

time and were later used to develop contamination limits for the ISS and the next generation of crewed vehicles.

Microbial growth in the closed environment of spacecraft can lead to a wide variety of adverse effects including infections as well as the release of volatile organics, allergens, and toxins. Biodegradation of critical materials, life support system fouling, and bio-corrosion represent other potential microbial-induced problems. Shuttle crew members sometimes reported dust in the air and occasional eye irritation. In-flight monitoring showed increased bacterial levels in the shuttle air as the number of days in space increased. Dust, microbes, and even water droplets from a simple

### Adverse Effects of Microorganisms

- Infectious diseases
- Toxin production
- Plant diseases
- Allergies
- Food spoilage
- Volatile release
- Material degradation
- Immune alteration
- Environmental contamination

*Astronauts Megan McArthur, Michael Massimino (center), and Andrew Feustel prepare to eat a meal on the middeck of Atlantis (STS-125 [2009]).*



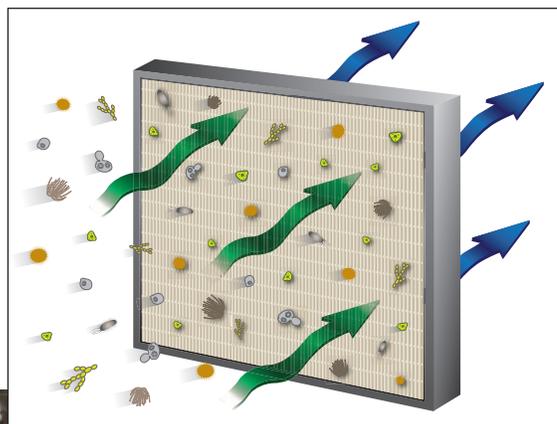


sneeze settle out on Earth. The human body alone sheds about 1 billion skin cells every week. Particles remain suspended in space and carry microorganisms and allergens that pose a health risk to the crew.

The shuttle's air filters were designed to remove particles greater than 70 micrometers. The filters removed most skin cells (approximately 100 micrometers) and larger airborne contaminants (e.g., lint); however, they did not quickly remove smaller contaminants such as bacteria, viruses, and particulates. When the shuttle was modified for longer flights of up to 2 weeks, an auxiliary cabin air cleaner provided filtration that removed particles over 1 micrometer. As the air recirculated through the vehicle, the filter captured skin cells, lint, microorganisms, and other debris. This resulted in much-improved air quality. These high-efficiency particulate air (HEPA) filters (99.97% efficient at removing particles >0.3 micrometers) provide dust- and microbe-free air. This led to the inclusion of HEPA filters in the Air Revitalization System on the ISS where monitoring has shown that air quality has been maintained below stringent microbial requirements. HEPA filters are also planned for other crewed vehicles.

Microbial growth can result in volatile chemicals that can produce objectionable odors or irritants. For example, during the STS-55 (1993) mission, the crew reported a noxious odor that was later found by extensive ground studies to be a mixture of three dimethyl sulfides resulting from the bacterial metabolism of urine in a waste storage container.

*As illustrated, a high-efficiency particulate air (HEPA) filter removes particles from recirculated air, resulting in improved air quality. The HEPA filter in the air-purification system on the International Space Station (ISS), as pictured below, is of a higher quality than purification systems used in offices and homes.*



These challenges provided opportunities for improvements that served as “lessons learned,” which were applied to all future missions. Lessons learned from the shuttle experiences led to NASA’s current approach of prevention first and mitigation second. Many microbiological risks associated with living in space can be prevented or mitigated to acceptable levels through engineering approaches. Prevention strategy begins with the design phase and includes steps that discourage excessive microbial growth. Use of antimicrobial materials,

maintaining relative humidity below 70%, avoiding condensation buildup, implementing rigorous housekeeping, maintaining air and water filtration, and judiciously using disinfectants are effective steps limiting the adverse effects of microorganisms. In all, the microbiological lessons learned from the Space Shuttle era resulted in improved safety for all future spacecraft.



## Astronaut Health Care

Astronaut health care includes all issues that involve flight safety, physiological health, and psychological health.

During the Space Shuttle Program, space medicine was at the “heart” of each issue.

Space medicine evolved during the shuttle’s many transitional phases, from the experimental operational test vehicle to pre-Challenger (1986) accident, post-Challenger accident, unique missions such as Department of Defense and Hubble, Spacelab/Spacehab, Extended Duration Orbiter Project,

Shuttle–Mir, Shuttle-International Space Station (ISS), post-Columbia (2003) accident and, finally, the ISS assembly completion. All of these evolutionary phases required changes in the selection of crews for spaceflight, preparation for spaceflight, on-orbit health care, and postflight care of the astronauts.

Astronauts maintained their flight status, requiring both ambulatory and preventive medical care of their active and inactive medical conditions. Preflight, on-orbit, and postflight medical care and operational space medicine training occurred for all flights. The medical team worked with

mission planners to ensure that all facets of coordinating the basic tenets of personnel, equipment, procedures, and communications were included in mission support. During the shuttle era, the Mission Control Center was upgraded, significantly improving communications among the shuttle flight crew, medical team, and other flight controllers with the flight director for the mission. Additionally, the longitudinal study of astronaut health began with all medical data collected during active astronaut careers. NASA used post-retirement exams, conducted annually, to study the long-term effect of short-duration spaceflight on crews.

## Space Adaptation Syndrome

The first thing an astronaut noticed was a fluid shift from his or her lower extremities to his or her torso and upper bodies, resulting in a facial fullness. Ultimately, this fluid shift caused a stretch on the baroreceptors in the arch of the aorta and carotid arteries and the astronaut would lose up to 1.5 to 2 L (1.6 to 2.1 qt) of fluid.

Secondly, over 80% of crew members experienced motion sickness, from loss of appetite to nausea and vomiting. Basic prevention included attempting to maintain an Earth-like orientation to the vehicle. Also, refraining from exaggerated movements helped. If symptoms persisted despite preventive measures, medications in an oral, suppository, or injectable form were flown to treat the condition.

The next thing crew members noticed was a change in their musculoskeletal system. In space, the human body experiences a lengthening and stretching of tendons and ligaments that hold bones, joints, and muscles together. Also, there was an unloading of the extensor muscles that included the back of the neck and torso, buttocks, and back of the thighs and calves. Preventive measures and treatment included on-orbit exercise, together with pain medications.

Additional changes were a mild decrease in immune function, smaller blood cell volume, and calcium loss. Other problems included headache, changes in visual acuity, sinus congestion, ear blocks, nose bleeds, sore throats, changes in taste and smell, constipation, urinary infections and difficulty in urination, fatigue, changes in sleep patterns with retinal flashes during sleep, minor behavioral health adjustment reactions, adverse reactions to medications, and minor injuries.

## Astronaut Selection and Medical Standards

Due to increasing levels of flight experience and changes in medical delivery, medical standards for astronaut selection evolved over the shuttle’s 30 years, as it was important that the selected individuals met certain medical criterion to be considered as having the “right stuff.” The space agency initially adopted these standards from a combination of US Air Force, US Navy, and Federal Aviation Administration as well as previous standards from the other US space programs. The shuttle medical standards were designed to support short-duration spaceflights of as many as 30 days. NASA medical teams, along with experts in aerospace medicine and systems specialties, met at least every 2 years to review and update standards according to a combination of medical issues related to flights and the best evidence-based medicine at that time. These standards were very strict for selection, requiring optimum health, and they eventually led to



the ISS medical requirements for long-duration spaceflight.

Preventive medicine was the key to success. Astronauts had an annual spaceflight certification physical exam to ensure they remained healthy for spaceflight, if assigned. Also, if a potential medical condition or problem was diagnosed, it was treated appropriately and the astronaut was retained for spaceflight. Medical exams were completed 10 days prior to launch and again at 2 days prior to launch to ensure that the astronaut was healthy and met the Flight Readiness Review requirements for launch. Preventive health successfully kept almost 99% of the astronauts retained for spaceflight duties during their careers with NASA.

### **Crew Preparation for Flight**

Approximately 9 months prior to each shuttle flight, the medical team and flight crew worked together to resolve any medical issues. The flight medical team provided additional medical supplies and equipment for the crew's active and inactive medical problems.

Spaceflight inspired some exceptional types of medical care. Noise was a hazard and, therefore, hearing needed to be monitored and better hearing protection was included. Due to the presence of radiation, optometry was important for eye health and for understanding the impact of radiation exposure on cataract development. Also, in space visual changes occurred with elongation of the eye, thus requiring special glasses prescribed for flight. All dental problems needed to be rectified prior to flight as well. Behavioral health counseling was also available for the crews and their families, if required. This program, along with on-orbit support, provided the advantage of improved

procedures and processes such as a family/astronaut private communication that allowed the astronaut another avenue to express concerns.

Over the course of the Space Shuttle Program, NASA provided improved physical conditioning and rehabilitation medicine throughout the year to keep crews in top physical shape. Before and during all shuttle flights, the agency provided predictions on solar activity and accumulation of the radiation astronauts received during their careers to help them limit their exposure.

Prior to a shuttle mission, NASA trained all astronauts on the effects of microgravity and spaceflight on their bodies to prepare them for what to expect in the environment and during the physiological responses to microgravity. The most common medical concerns were the space adaptation syndrome that included space motion sickness and the cardiovascular, musculoskeletal, and neurovestibular changes on orbit. Other effects such as head congestion, headaches, backaches, gastrointestinal, genitourinary, crew sleep, rest, fatigue, and handling of injuries were also discussed. The most common environmental issues were radiation, the biothermal considerations of heat and cold stress, decompression sickness from an extravehicular activity (EVA), potable water contamination, carbon dioxide (CO<sub>2</sub>), and other toxic exposures. Re-entry-day (return to Earth) issues were important because the crew transitioned quickly from microgravity into a hypergravity, then into a normal Earth environment. Countermeasures needed to be developed to overcome this rapid response by the human body. These countermeasures included the control of cabin temperature, use of the g-suit, and entry fluid loading, which helped restore fluid in the plasma volume that

was lost on orbit during physiological changes to the cardiovascular system. It was also important to maximize the health and readaptation of the crew on return to Earth in case emergency bailout, egress, and escape procedures needed to be performed.

The addition of two NASA-trained crew medical officers further improved on-orbit medical care. Training included contents of the medical kits with an understanding of the diagnostic and therapeutic procedures contained within the medical checklist. These classes were commonly referred to as "4 years of medical school in three 2-hour sessions." Crew medical officers learned basic emergency and nonemergency procedures common to spaceflight. This training included how to remove foreign bodies from the eye; treat ear blocks and nose bleeds; and start IVs and give medications that included IV, intramuscular, and subcutaneous injections and taught the use of oral and suppository intake. Emergency procedures included training in cardiopulmonary resuscitation, airway management and protection, wound care with Steri-Strip™ and suture repair, bladder catheterization, and needle thoracentesis. NASA taught special classes on how to mitigate the possibility of decompression sickness from an EVA. This incorporated the use of various EVA prebreathe protocols developed for shuttle only or shuttle-ISS docking missions. Crews were taught to recognize decompression sickness and how to medically manage this event by treating and making a disposition of the crew member if decompression sickness occurred during an EVA.

Environmental exposure specialty classes included the recognition and management of increased CO<sub>2</sub> exposure, protection and monitoring in case of radiation exposure from either artificial or solar particle events, and the



## Shuttle Medical Kit

The Shuttle Orbiter Medical System had generic and accessory items and provided basic emergency and nonemergency medical care common to spaceflight. The contents focused on preventing illnesses and infection as well as providing pain control. It also provided basic life support to handle certain life-threatening emergencies, but it did not have advanced cardiac life support capabilities. Initially, it included two small kits of emergency equipment, medications, and bandages; however, this evolved into a larger array of sub packs as operational demands required during the various phases of the program. The generic equipment remained the same for every flight, but accessory kits included those mission-specific items tailored for the crew's needs. Overall, the Shuttle Orbiter Medical System included: a medical checklist that helped the on-board crew medical officers diagnose and treat on-orbit medical problems; an airway sub pack; a drug sub pack; an eye, ear, nose, throat, and dental sub pack; an intravenous sub pack; saline supply bags; a trauma sub pack; a sharps container; a contamination cleanup kit; patient and rescue restraints; and an electrocardiogram kit.



biothermal consideration of heat stress in case the Orbiter lost its ability to maintain cooling. Toxicology exposure specialty classes focused on generic toxic compounds unique to the Orbiter and included hypergolic exposure to

hydrazines and nitrogen tetroxide, ammonia, and halogenated hydrocarbons such as halon and Freon®. Certain mission-specific toxic compounds were identified and antidotes were flown in case of crew

exposure to those compounds. NASA trained crew members on how to use the toxicology database that enabled them to readily identify the exposed material and then provide protection to themselves during cleanup of toxic compounds using a specialty contamination cleanup kit. Astronauts were also trained on fire and smoke procedures such as the rapid quick-don mask for protection while putting out the fire and scrubbing the cabin atmosphere. In such an incident, the atmosphere was monitored for carbon monoxide, hydrogen cyanide, and hydrogen chloride. When those levels were reduced to nontoxic levels, the masks were removed.

The potable water on the shuttle was monitored 15 and 2 days preflight to ensure quality checks for iodine levels, microbes, and pH. Crews were instructed in limiting their iodine (bacteriostatic agent added to stored shuttle water tank) intake by installing/reinstalling a galley iodine-reduction assembly device each day that limited their intake of iodine from the cold water. The crews also learned how to manage the potable water tank in case it became contaminated on orbit.

Over the course of the program, NASA developed Flight Rules that covered launch through recovery after landing and included risky procedures such as EVAs. These rules helped prevent medical conditions and were approved through a series of review boards that included NASA missions managers, flight directors, medical personnel, and outside safety experts. The Flight Rules determined the preplanned decision on how to prevent or what to do in case something went wrong with the shuttle systems. Other controlled activities were rules and constraints that protected and maintained the proper workload, rest, and sleep prior to flight and for on-orbit operations during the presleep,



work, and post-sleep periods. The flight-specific sleep and work schedule was dependent on the launch time and included the use of bright and dim lights, naps, medications, and shifts in sleep and work patterns. NASA developed crew schedules to prevent crew fatigue—an important constraint for safety and piloted return.

Although implemented in the Apollo Program, preflight crew quarantine proved to be essential during the Space Shuttle Program to prevent infectious disease exposure prior to launch. The quarantine started 7 days prior to launch. At that point, all crew contacts were monitored and all contact personnel received special training in the importance of recognizing the signs and symptoms of infectious disease, thus limiting their contact with the flight crew if they became sick. This program helped eliminate the exposure of an infectious disease that would delay launch and was successful in that only one flight had to be delayed because of a respiratory illness.

### Readiness for Launch and On-orbit Health Care

Launch day is considered the most risky aspect of spaceflight. As such, medical teams were positioned to work directly with mission managers as well as the shuttle crew during this critical stage. On launch day, one crew medical doctor was stationed in the Launch Control Center at Kennedy Space Center (KSC) with KSC medical emergency care providers. They had direct communication with Johnson Space Center Mission Control, Patrick Air Force Base located close to KSC, alternate landing sites at Dryden Flight Research Center/Edwards Air Force Base, White Sands Space Harbor, and transoceanic abort landing medical teams. Another crew medical doctor was pre-staged near a triage site with

## Crew Transport Vehicle



Prior to the 1990s' Extended Duration Operations Program, immediate postflight care was conducted

in the “white room” or on a small stairwell platform that mated with the port-side hatch of the shuttle. Typically, astronaut support personnel, a “suit” technician, and the crew medical team entered the shuttle, postlanding. If a medical condition occurred and a crew member had problems readapting to the Earth environment, this care was conducted in the shuttle interior or on the platform of the “white room” stairwell. One major improvement to landing-day medical care was the change to a mobile postflight crew transport vehicle. This vehicle was redesigned to mate with the Orbiter and provided private transport of the crew to a location where they could receive better care, if required. The vehicle was outfitted with lounge chairs, a rest room, gurneys, and medical supplies. The crew could first be stabilized. Then, those who didn't need to remain on board for research testing could perform a crew walk around the Orbiter.

The crew transport vehicle was first used with STS-40 at Dryden Flight Research Center (DFRC), California, in 1991 and supported all subsequent shuttle flights at both DFRC and Kennedy Space Center, Florida.

the KSC rescue forces and trauma teams at a site determined by wind direction. Other forces, including military doctors and US Air Force pararescuers in helicopters, stood on “ready alert” for any type of launch contingency.

Once launch occurred and the crew reached orbit in just over 8 minutes, physiologic changes began. Every crew member was unique and responded to these changes differently on a various scale.



All medical conditions were discussed during a private medical communication with the crew every flight day. The results at the end of a discussion were one of the following: no mission impact (the majority); possible mission impact; or mission impact. With possible mission impacts, further private discussion with the crew and flight director, other crew members, and other medical care specialists occurred. Fortunately for the program, all possible mission impacts were resolved with adjustments to the timeline and duties performed by the crew so the mission could continue to meet its objectives. If a mission impact were to occur, changes would be made public but not the specifics of those changes. Due to the Medical Privacy Act of 1974, details of these private medical conferences could not be discussed publicly.

Private family communication was another important aspect, psychologically, of on-orbit health care. Early in the program, this was not performed but, rather, was implemented at the start of the Extended Duration Orbiter Medical Project (1989-1996) and involved flights of 11 days or longer.

The second riskiest time of spaceflight was returning to Earth. To overcome hypotension or low blood pressure during re-entry, the crew employed certain countermeasures. The crew would fluid load to restore the lost plasma volume by ingesting 237 ml (8 oz) of water with two salt tablets every 15 minutes, starting 1 hour prior to the time of deorbit ignition and to finish this protocol by entry interface (i.e., the period right before the final return stage) for a total fluid loading time of 90 minutes. Body weight determined the total amount ingested. After the Challenger accident, NASA developed a launch and re-entry suit that transitioned from the standard Nomex® flight suit, to a partial pressure

suit, then on to a full pressure suit called the advanced crew escape suit. An incorporated g-suit could be used to compress lower extremities and the abdomen, which prevented fluid from accumulating in those areas. Another post-Challenger accident lesson learned was to cool the cabin and incorporate the liquid cooling within the launch and re-entry suit to prevent heat loads that could possibly compromise the landing performance of the vehicle by the commander and pilot (second in command). Finally, each crew member used slow, steady motions of his or her head and body to overcome the neurovestibular changes that occurred while transitioning from a microgravity to an Earth environment. All items were important that assisted the crew in landing the vehicle on its single opportunity in a safe manner.

### **Postflight Care**

Once the landed shuttle was secured from any potential hazards, the medical team worked directly with returning crew members. Therefore, medical teams were stationed at all potential landing sites—KSC in Florida, Dryden Flight Research Center in California, and White Sands in New Mexico.

When the crew returned to crew quarters, they reunited with their families and then completed a postflight exam and mini debrief. Crew members were advised not to drive a vehicle for at least 1 day and were restricted from aircraft flying duties due to disequilibrium—problems with spatial and visual orientation. NASA performed another postflight exam and a more extensive debrief at return plus 3 days and, if passed, the crew member was returned to aircraft flight duties. Mission lessons learned from debriefs were shared with the other crew medical teams, space medicine researchers, special project engineers, and the flight directors. All of these

lessons learned over time, especially during the transitional phases of the program, continued to refine astronaut health and medical care.

### **Accidents and Emergency Return to Earth**

Main engine or booster failures could have caused emergency returns to KSC or transoceanic abort landing sites. NASA changed its handling of post-accident care after the two shuttle accidents. Procedures specific for the medical team were sessions on emergency medical services with the US Department of Defense Manned Spaceflight Support Office and included search and rescue and medical evacuation. This support and training evolved tremendously after the Challenger and Columbia accidents, incorporating lessons learned. It mainly included upgrades in training on crew equipment that supported the scenarios of bailout, egress, and escape.

### **The Future of Space Medicine**

NASA's medical mission continues to require providing for astronaut health and medical care. Whatever the future milestones are for the US space program, the basic tenets of selecting healthy astronaut candidates by having strict medical selection standards and then retaining them through excellent preventive medical care are of utmost importance. Combining these with the operational aspects of coordinating all tenets of understanding the personnel, equipment, procedures, and communications within the training to prepare crews for flight will enhance the success of any mission.

At the closing stages of the Space Shuttle Program, no shuttle mission was terminated or aborted because of a medical condition, and this was a major accomplishment.



# The Space Shuttle: A Platform That Expanded the Frontiers of Biology

Kenneth Souza

*The Space Shuttle brought a new dimension to the study of biology in space. Prior to the shuttle, scientists relied primarily on uncrewed robotic spacecraft to investigate the risks associated with venturing into the space environment. Various biological species were flown because they were accepted as models with which to study human disease and evaluate human hazards. The results from the pioneering biological experiments aboard uncrewed robotic spacecraft not only provided confidence that humans could indeed endure the rigors of spaceflight, they also formed the foundation on which to develop risk mitigation procedures; i.e., countermeasures to the maladaptive physiological changes the human body makes to reduced gravity levels. For example, the musculoskeletal system reacts by losing mass. This may pose no hazard in space; however, on returning to Earth after long spaceflights, such a reaction could result in an increased risk of bone fractures and serious muscle atrophy.*

*Unfortunately, most biological research in uncrewed spacecrafts was limited to data that could only be acquired before and/or after spaceflight. With crew support of the experiments aboard the Space Shuttle and Spacelab, and with adequate animal housing and lab support equipment, scientists could train the crew to obtain multiple biospecimens during a flight, thus providing windows into the adaptation to microgravity and, for comparison, to samples obtained during readaptation to normal terrestrial conditions postflight.*

*With the Space Shuttle and its crews, earthbound scientists had surrogates in orbit—surrogates who could be their eyes and hands within a unique laboratory. The addition of Spacelab and Spacehab, pressurized laboratory modules located in the shuttle payload bay, brought crews and specialized laboratory equipment together, thus enabling complex interactive biological research during spaceflight. Crew members conducted state-of-the-art experiments with a variety of species and, in the case of human research, served as test subjects to provide in-flight measurements and physiological samples.*

*In addition to the use of biological species to evaluate human spaceflight risks, research aboard the shuttle afforded biologists an opportunity to examine the fundamental role and influence of gravity on living systems. The results of such research added new chapters to biology textbooks. Life on Earth originated and evolved in the presence of a virtually constant gravitational field, but leaving our planet of origin creates new challenges that living systems must cope with to maintain the appropriate internal environment necessary for health, performance, and survival.*



## **How Does Gravity Affect Plants and Animals?**

Throughout the course of evolution, gravity has greatly influenced the morphology, physiology, and behavior of life. For example, a support structure—i.e., the musculoskeletal system—evolved to support body mass as aquatic creatures transitioned to land. To orient and ambulate, organisms developed ways to sense the gravity vector and translate this information into a controlled response; hence, the sensory-motor system evolved. To maintain an appropriate blood supply and pressure in the various organs of the mammalian body, a robust cardiovascular system developed. Understanding how physiological systems sense, adapt, and respond to very low gravity cannot be fully achieved on the ground; it requires the use of spaceflight as a tool. Just as we need to examine the entire light spectrum to determine how the visual organs of living systems work, so too we must use the complete gravity spectrum, from hypogravity to hypergravity, to understand how gravity influences life both on and off the Earth.

Space biologists have identified and clarified the effects of spaceflight on a few representative living systems, from the cellular, tissue, and system level to the whole organism. NASA achieved many “firsts” as well as other major results that advanced our understanding of life in space and on Earth. The agency also achieved many technological advances that provided life support for the study of the various species flown.



**Baruch Blumberg, MD**  
Nobel Prize winner in medicine, 1976.  
Professor of Medicine  
Fox Chase Cancer Center.  
Former director of Astrobiology  
Ames Research Center, California.

*“The United States and other countries are committed to space travel and to furthering the human need to explore and discover. Since April 12, 1981, the*

*shuttle has been the major portal to space for humans; its crews have built the International Space Station (ISS), a major element in the continuum that will allow humans to live and work indefinitely beyond their planet of origin. The shuttle has provided the high platform that allows observations in regions that were previously very difficult to access. This facilitates unique discoveries and reveals new mysteries that drive human curiosity.*

*“In the final paragraph of Origin of Species Darwin wrote:*

*There is grandeur in this view of life, with its several powers, having been originally breathed by the Creator into a few forms or into one; and that, whilst this planet has gone circling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved.*

*“The shuttle and the ISS now provide a means to study life and its changes without the constraints of gravity. What will be the effect of this stress never before experienced by our genome and its predecessors (unless earlier forms of our genes came to Earth through space from elsewhere) on physiology, the cell, and molecular biology? Expression of many genes is altered in the near-zero gravity; how does this conform to the understanding of the physics of gravity at molecular and atomic dimensions?*

*“In time, gravity at different levels, at near-zero on the ISS, at intermediate levels on the moon and Mars, and at one on Earth, can provide the venues to study biology at different scales and enlarge our understanding of the nature of life itself.”*



## Gravity-sensing Systems— How Do Plants and Animals Know Which Way Is Down or Up?

As living systems evolved from simple unicellular microbes to complex multicellular plants and animals, they developed a variety of sensory organs that enabled them to use gravity for orientation. For example, plants developed a system of intracellular particles called statoliths that, upon seed germination, enabled them to sense the gravity vector and orient their roots down into the soil and their shoots up toward the sun. Similarly, animals developed a variety of sensory systems (e.g., the vestibular system of the mammalian inner ear) that enabled them to orient with respect to gravity, sense the body's movements, and transduce and transmit the signal to the brain where it could be used together with visual and proprioceptive inputs to inform the animal how to negotiate its environment.

### Why Do Astronauts Get Motion Sickness in Spaceflight?

One consequence of having gravity-sensing systems is that while living in microgravity, the normal output from the vestibular system is altered, leading to a confusing set of signals of the organism's position and movement. Such confusion is believed to result in symptoms not too different from the typical motion sickness experienced by seafarers on Earth. This affliction, commonly termed "space motion sickness," affects more than 80% of astronauts and cosmonauts during their first few days in orbit. Interestingly, one of



*STS-40 (1991) payload specialist Millie Hughes-Fulford working with the Research Animal Holding Facility.*



the two monkeys flown in a crewed spacecraft, the Space Transportation System (STS)-51B (1985) Spacelab-3 mission, displayed symptoms resembling space motion sickness during the first few days of spaceflight.

The basic process of space motion sickness became one of the main themes of the first two dedicated space life sciences missions: STS-40 (1991) and STS-58 (1993). Scientists gained insights into space motion sickness by probing the structural changes that occur in the vestibular system of the mammalian balance organs. Using rodents, space biologists learned for the first time that the neural hair cells of the vestibular organ could change relatively rapidly to altered gravity. Such neuroplasticity was evident in the increased number of synapses (specialized junctions through which neurons signal to each other)

between these hair cells and the vestibular nerve that occurred as the gravity signal decreased. In effect, the body tried to turn up the gain to receive the weaker gravitational signal in space. This knowledge enabled medical doctors and crew members to have a better understanding of why space motion sickness occurs.

### Is Gravity Needed for Successful Reproduction?

#### *Amphibian Development*

Studies of the entire life span of living systems can provide insights into the processes involved in early development and aging. The Frog Embryology Experiment flown on STS-47 (1992) demonstrated for the first time that gravity is not required for a vertebrate species, an amphibian, to ovulate,



fertilize, achieve a normal body pattern, and mature to a free-swimming tadpole stage. This experiment put to rest the “gravity requirement” question that had been debated by embryologists since the late 19th century.

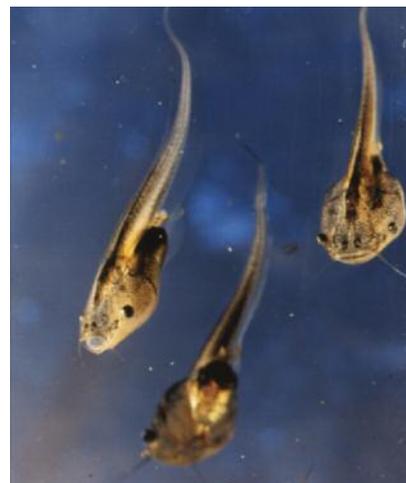
In Earth gravity, frog eggs, when shed, have a bipolar appearance; i.e., the spherical egg has a darkly pigmented hemisphere containing the nucleus and much of the cell machinery needed for development while the opposite, lightly pigmented hemisphere is rich in yolk that provides the energy to drive the cell machinery during early development. Shortly after being shed, the eggs can be fertilized by sperm released by an adjoining male frog. Once fertilized, a membrane lifts off the egg surface and the egg responds to gravity by orienting the dense yolk-rich hemisphere down and the darkly pigmented hemisphere up with respect to the gravity vector. This geotropic response was what spurred early embryologists to interfere with

egg rotation and thereby tried to determine whether the response to gravity was required for normal development. Unfortunately, research on the ground yielded ambiguous results due primarily to the trauma imparted to the eggs by the scientists’ attempts to interfere with rotation.

During the STS-47 flight, adult female frogs (*Xenopus laevis*) were injected with hormone to induce the shedding of eggs, followed by the addition of a sperm suspension. Half of a group of fertilized eggs were placed in special water-filled chambers and on a rotating centrifuge to provide an acceleration environment equivalent to terrestrial gravity. The other half were placed in the same type of water-filled chambers, but in a temperature-controlled incubator and were kept in a microgravity environment. Samples of developing embryos were taken during the flight to capture important developmental stages for examination postflight. Some were returned to



*Fertilized frog eggs (above) and free-swimming tadpoles (below).*



*Astronaut Mark Lee working on the Frog Embryology Experiment in the General Purpose Work Station during the STS-47 (1992) mission.*

Earth as free-swimming tadpoles. The results of the experiment ended the centuries-old debate as to whether gravity is needed for successful reproduction, and demonstrated for the first time that a vertebrate species could be fertilized and develop normally to a free-swimming stage in the virtual absence of gravity. It remains to be seen, however, whether metamorphosis, maturation, and a complete life cycle of an amphibian or other complex organisms can occur in the absence of gravity.

In summary, for the first time, a vertebrate species was fertilized and developed through to a free-swimming stage in the virtual absence of gravity.



**William Thornton, MD**

*Principal investigator for the first in-flight studies of space motion sickness on shuttle. Astronaut on STS-8 (1983) and STS-51B (1985).*

**Bring 'em Back Alive**

**The First Human Flight in Space with an Animal**

*“My training for the Spacelab 3 animal payload began as a toddler in North Carolina, surrounded by and growing up with a great variety of domestic and wild animals. Their humane treatment was my first lesson.*

*“After additional years of formal and informal education in medicine and biophysics, I used my training for research on space motion sickness. For some 18 months during the first shuttle flights, we completed human studies, which produced an array of first-time procedures in the US space program, including evoked potentials, coordination, complex reaction time, gastrointestinal activity and pressure, ambulatory blood pressure, and electrocardiograms, etc. These experiments answered some urgent operational questions and provided points of departure for the more formal studies that followed.*

*“Like so much of medical science, elemental knowledge of our nervous system comes from animal studies on Earth. On my first flight (STS-8 in 1983), 24 rats were flown in a research animal holding facility. But, to fly animals for study in the small, enclosed environment of the shuttle is a complex challenge that required years of preparation.*



*Dr. Thornton is taking care of one of the two squirrel monkeys on STS-51B.*

*“Finally flying on Challenger, we were able to open the cage inspection ports. All was well except for the monkey who had been a laboratory favorite (this is the animal in the photo) but who was now in deep withdrawal. He didn't eat or drink for 2 days and by the third day, dehydration was real. I used some tricks learned while feeding wild pets and he took a banana pellet and another—and more and more, then cage food.*

*“We returned with all animals alive and well and a great deal of experience subsequently incorporated into the shuttle legacy of astronauts and animals in space. Now, those of us who work with humans and space motion sickness have such remarkable aid as the molecular and ultra-microscopic studies from animals in NeuroLab, another shuttle legacy.”*

**Animal Development**

Studies with rodents aboard the Space Shuttle identified stages of early mammalian development that are sensitive to altered gravity. They

also provided insights into what might happen if humans experience abnormal gravity levels during early development. Pregnant rats on STS-66 (1994) and STS-70 (1995) showed that spaceflight resulted in striking

changes in the structure of the fetal balance organ—the vestibular system. On STS-90 (1998), rat pups were launched at 8 or 14 days *postpartum*. After 16 days in microgravity, their sensorimotor functions were tested



within several hours of landing; e.g., walking, and righting (rolling over). Postflight, the righting response of postnatal pups was profoundly deficient compared to ground control animals, suggesting that removal of gravitational cues during early postnatal development can significantly alter inherent patterns of behavior. In addition, neonatal animals exposed to microgravity during this Neurolab mission failed to undergo normal skeletal muscle growth and differentiation, suggesting that gravity stimuli are essential for generating the structure needed to perform basic ambulatory and righting movements when subjected, postflight, to terrestrial gravity.

## Plant Biology

### Germination

The importance of gravity in the germination and development of plants has been observed and studied for centuries; however, it wasn't possible to unravel how a plant detects and responds to gravity until access to space was achieved. NASA had to develop specialized equipment to grow plants and study their response to gravity. The agency developed a plant growth unit to fit within a shuttle middeck locker. This unit provided light, water, and an appropriate substrate to support plant growth. On the STS-51F (1985) mission, seedlings were grown in enclosed chambers within the plant growth unit; i.e., mung beans (*Vigna radiata*), oats (*Avena sativa*), and pine (*Pinus elliotti*). Mung beans and oat seeds were planted 16 hours before launch and germination occurred in space. Pine seedlings were 4 or 10 days post-germination at



The Biomass Production System installed on STS-111 (2002) carrying plants grown in the International Space Station (ISS) for return to Earth. ISS Flight Engineer Dan Burch (pictured) conducted all of the plant experiments.



Multiple generations of plants grew in spaceflight for the first time. Examples include Apogee Wheat (top) and Brassica rapa (bottom).

launch. Although the mung bean and oat seeds germinated in orbit, root growth was somewhat disoriented and oats grew more slowly during spaceflight. In addition, the amount of lignin, a biochemical component of a plant's "skeletal" system, was significantly reduced in all three species, indicating that gravity is an important factor in lignification necessary for plant structure.

### Plant Growth

Another pioneering experiment in the study of plant responses to gravity was the Gravitational Threshold Experiment flown on the STS-42 (1992) mission. It tested plant sensitivity to altered gravitational fields during spaceflight. The Gravitational Plant Physiology Facility was built to support plant growth and stimulate plants with different levels of gravity using four



centrifuge rotors contained within the facility. Two centrifuge rotors (culture rotors) were used to grow small seedlings in a 1 gravitational force (1g) environment (normal terrestrial level). The other two rotors provided gravity stimulations of varying strength and duration (test rotors). After stimulation on the test rotors, images of the seedling responses were captured on video recorders. This research identified for the first time the threshold stimulus for a biological response to gravity. Oat seedlings were used in the experiment and, when the seedlings reached the proper stage of growth on the 1g centrifuge rotor, an astronaut transferred them to the test centrifuge to expose them to a g-stimulus for different durations and intensities. The threshold was found to be very low—about 15 or 20 g-seconds; i.e., it took a force of 1g applied for 15 to 20 seconds to generate a plant response.

Following the pioneering plant experiments, NASA and others developed equipment with a greater range of capabilities, thus enabling more complex and sophisticated scientific experiments. This equipment included the European Space Agency's Biorack flown on Spacelabs; the Russian Svet and Lada systems

flown on Mir and the International Space Station (ISS), respectively; NASA's Biomass Production System; and the European Modular Cultivation System flown on the ISS. This latter device enabled more in-depth studies of plant geotropisms than had been possible in any of the previous flight experiments with plants.



**Arabidopsis plant.** This small plant is related to cabbage and mustard and is widely used as a model for plant biology research.

*Arabidopsis* seedlings were subjected to 1g in space on a Biorack centrifuge while a separate group was held under microgravity conditions. The experiments provided evidence that intracellular starch grains (statoliths) sediment in the presence of a gravity stimulus and influence how plants are oriented with respect to the gravity vector. Experiments within the Biomass Production System revealed much about growing plants within spaceflight

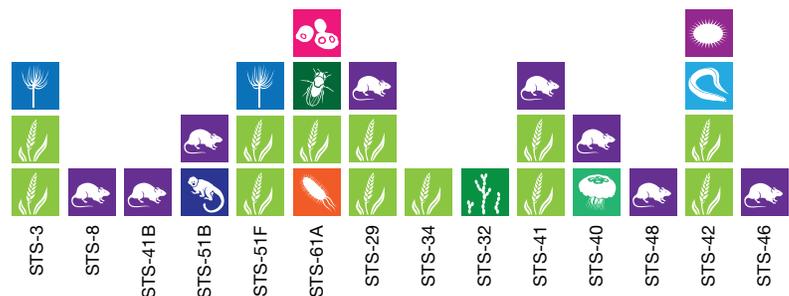
hardware, particularly about plant metabolism in the absence of normal terrestrial gravity. Biomass Production System investigators concluded that plant photosynthesis and transpiration processes did not differ dramatically from those on the ground.

### Multiple Generations of Growth— Fresh Foods

The early shuttle experiments with plants focused on basic questions about gravity-plant interactions. The scientific results as well as the knowledge gained in the design and fabrication of plant growth habitats greatly contributed to the development of the next generation of growth chambers. Russian investigators from the Institute of Biomedical Problems, Moscow, with support of US scientists and engineers, provided the equipment necessary to achieve multiple generations of plants in space. Multiple generations of wheat and mustard species were obtained during spaceflight on Mir and the ISS. In addition, a variety of edible vegetables were grown during spaceflight, demonstrating that plants can be used to provide fresh food supplements for future long-duration space exploration missions.

### Space Biology Payloads

Avian	Frog, Newt	Pine, Fir Seedlings
Bacteria	Fungi	Primate
Cells	Insect	Rodent
Fern	Jellyfish	Sea Urchin
Fish	Moss	Snail
Flowering Plant	Nematode	Yeast





## Bacteria More Dangerous in Space Environment

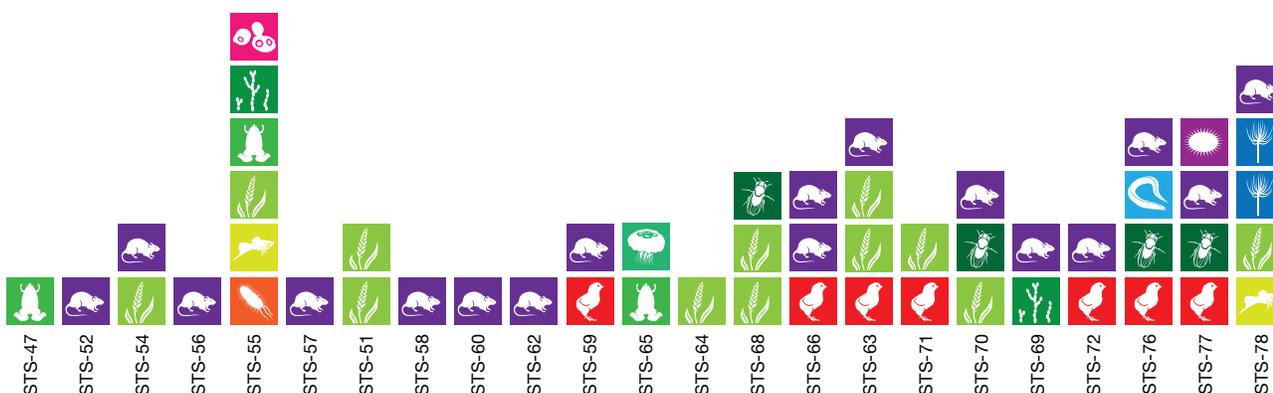
As reported by Cheryl Nickerson, the interplay between the human immune system and the invading microorganism determines whether infection and disease occur. Factors that diminish immune capability or increase the virulence of the microorganism will greatly increase the likelihood of disease.

To gain insight to this issue, investigators compared responses of the food-borne bacterial pathogen *Salmonella typhimurium*, grown in the microgravity of spaceflight, to otherwise identical ground-based control cultures. Interestingly, they found that the spaceflight environment profoundly changed the gene expression and virulence characteristics (disease-causing potential) of the pathogen in novel ways that are not observed when growing the cells with traditional culture methods. This work also identified a “master molecular switch” that appears to regulate many of the central responses of *Salmonella* to the spaceflight environment.

On both the STS-115 (2006) and the STS-123 (2008) shuttle missions, scientists investigated the spaceflight response of *Salmonella* grown in various growth media containing different concentrations of five critical ions. The effects of media ion composition on the disease-causing potential of *Salmonella* were dramatic. Flight cultures grown in media containing lower levels of the ions displayed a significant increase in virulence as compared to ground control cultures, whereas flight cultures grown in higher ion levels did not show an increase in virulence. The wealth of knowledge gained from these *Salmonella* gene expression and virulence studies provides unique insight into both the prevention of infectious disease during a spaceflight mission and the development of vaccines and therapeutics against infectious agents on Earth.



*Astronaut Heidemarie Stefanyshyn-Piper, in the middeck of the Space Shuttle Atlantis, activates the MICROBE experiment, which investigated changes to Salmonella virulence after growth in space.*





## Why Do Astronauts Get Weak Muscles and Bones?

### Muscles

The Space Transportation System (STS)-58 (1993) mission opened a new window on how weightlessness affects muscle structure and function. Previously, scientists knew that skeletal unloading (lack of gravity) resulted in the atrophy of muscle fibers. Until this flight, all of the skeletal muscles studied were obtained from humans or rats postflight, several hours after readapting to terrestrial gravity. Consequently, distinguishing the structural and biochemical changes made in response to microgravity from changes readapting to Earth postflight was very difficult. During the STS-58 mission, crew members obtained tissue samples from animals and processed these samples for detailed structural and biochemical analyses postflight, thus avoiding the effects of re-entry and readapting to Earth's gravity. Danny Riley of Wisconsin Medical College summed up how sampling in flight changed his understanding. "When we looked at muscle samples that we obtained from previous missions, we saw muscle atrophy and muscle lesions, small tears. Samples

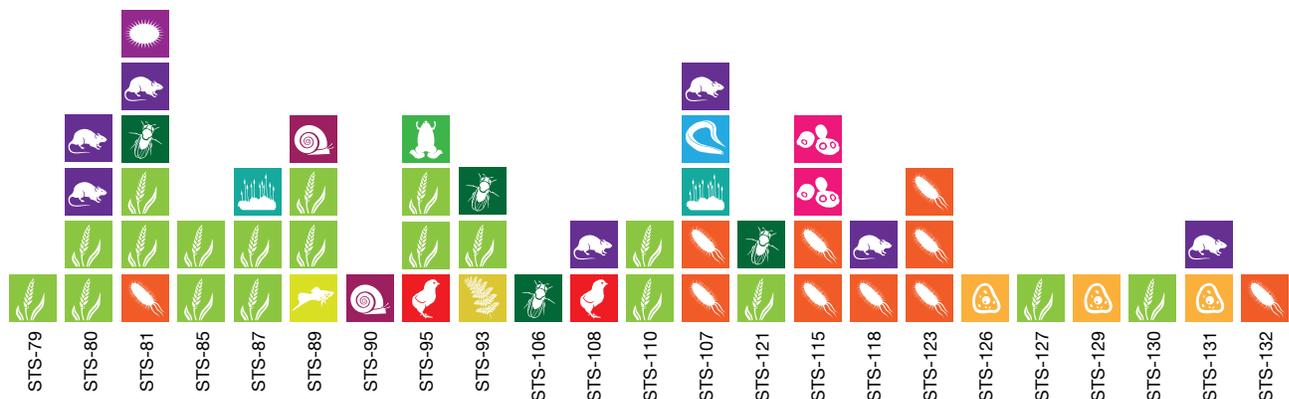
taken from rats during and following the STS-58 flight enabled us to determine that the atrophy was clearly a response to microgravity while the muscle lesions were a result of re-entry and readaptation stresses," Riley said.

For the STS-58 mission, muscle physiologists examined the contractile properties of rat muscles and demonstrated large changes that correlated well with the biochemical and morphological changes they had previously observed. As Ken Baldwin of the University of California at Irvine stated, "The uniqueness of performing spaceflight studies aboard STS-58 using the rodent model was that we discovered marked remodeling of both structure and function of skeletal muscle occurring after such a short duration in space. The results enabled scientists to better predict what could happen to humans if countermeasures (i.e., exercise) were not instituted early on in long-duration space missions."

The fundamental research with animals aboard the shuttle Spacelabs contributed markedly to the current understanding of the effects of spaceflight on skeletal muscle. The results laid the foundation for defining optimal countermeasures that minimize the atrophy that occurs in the human response to microgravity.

### Bones

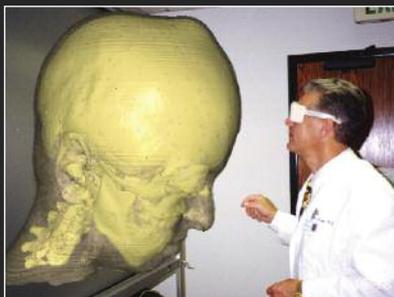
Skeletal bone, much like skeletal muscle, atrophies when unloaded. Bone mass loss as a consequence of skeletal unloading during spaceflight is a well-established risk for long-term human space exploration. A great deal of the insight into "why" and "how" bone mass loss occurs in flight resulted from research with rodents both on board the US Space Shuttle and the Russian Bion biosatellites. Such research revealed that bone formation becomes uncoupled from resorption (process of minerals leaving the bone) and normal bone mineral homeostasis is compromised. Consistent with several previous studies, results from the Physiological Systems Experiments series of payloads (STS-41 [1990], STS-52 [1992], STS-57 [1993], and STS-62 [1994]) showed that bone formation in the weight-bearing bones of male rats was inhibited by short-term spaceflight. Radial bone growth in the humerus (long bone in the arm or forelimb that runs from the shoulder to the elbow) was also decreased, though no changes in longitudinal bone growth in the tibia (shin bone in leg) were detected. These effects were associated with a decrease in the number and activity of bone-forming cells (osteoblasts). Results of experiments on board STS-58 and STS-78 (1996) provided further



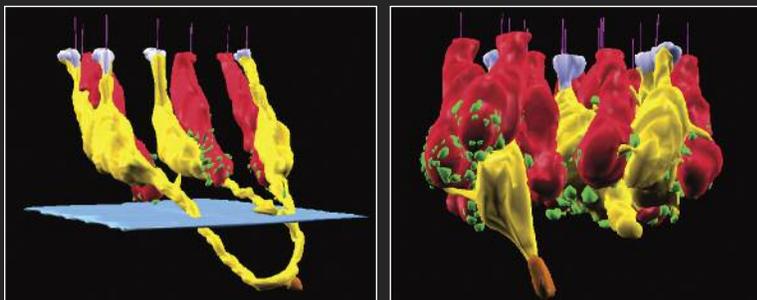


## New Technology for Three-dimensional Imaging

Rodent inner-ear hair cells are almost identical to human inner-ear hair cells. These cells are important for the vestibular system. Space biological research contributed novel technologies for diagnostic medicine on Earth. NASA developed three-dimensional (3-D) imaging software to facilitate and expedite the microscopic analysis of thin sections of the body's balance organ—the vestibular system of the inner ear. The software enabled reconstruction of the innervation pattern of the rodent's inner ear much faster than traditional manual methods. Not only did the technology greatly accelerate the analyses of electron microscopic images, it also was adapted to construct 3-D images from computerized axial tomography (CAT) and magnetic resonance imaging (MRI) scans of humans, providing surgeons with 3-D dynamic simulations for reconstructive breast cancer surgery, dental reconstruction, plastic surgery, brain surgery, and other delicate surgeries. Such simulations enable doctors to visualize and practice procedures prior to surgery, resulting in a much shorter time for the patient to be under anesthesia and a lower risk surgery.



*Surgical planning using 3-D virtual imaging software. Dr. Stephen Schendel, Stanford University.*



*3-D reconstructions of rodent inner-ear hair cells using Ross software.*

evidence of changes at both the structural and the gene expression levels associated with spaceflight-induced bone loss. Alterations also occurred in bone mineral distribution, ultrastructure and geometry, and mechanical properties as well as in site and gene-specific decreases in expression of bone matrix proteins (structural proteins with minerals attached). Taken together, these results suggest that significant tissue-specific alterations at the structural and molecular levels accompany bone loss in microgravity.

At the cellular level, spaceflight was also shown to affect bone, cartilage, and tendons, resulting in reduced matrix production or altered matrix composition.

How do bone cells sense and respond to changes in gravity? Some scientists suggest that certain cell types, when exposed to microgravity, reduce their activity or metabolism as well as the amount of new protein normally produced and enter a “resting” phase. This microgravity effect could be due to a direct effect on the mature differentiated cell (final cell type for a specific organ like bone; e.g., osteoblast) so that the cell generates some “signal” during spaceflight, thus driving the cell to enter a resting phase. Another possibility is that the cell division cycle is delayed so that cells simply develop into their differentiated state more slowly than normal. A series of experiments was flown on STS-118 (2007) and STS-126 (2008) that studied bone marrow cell (the progenitors of bone cells) population changes in microgravity



using mouse primary white blood cell (macrophage) cultures, respectively. The mouse study identified phenotypic (any observable characteristic or trait of an organism, such as its structure or function) shifts in the bone marrow cell subpopulations, including a subpopulation of macrophages.

On STS-95 (1998) scientists placed bone cartilage cells into cartridges carried in a special cell culture device built by the Walter Reed Army Institute for Research, Washington, D.C. Samples of these cells were collected on Flight Days 2, 4, 7, and 9. The media in which the cells grew were also collected on the same days, and the conversion of glucose to lactate in the media—a sign of metabolic activity—was determined postflight. Following flight, these cells were analyzed for their state of differentiation and parameters showing the cell cycle activity. The results strongly indicated that these cells were affected by flight. Flight cells were metabolically less active and produced fewer matrix components (necessary for structure) than the cells grown on the ground. In contrast to this, the flight cells showed a greater content of cyclins (proteins related to different stages of the cell cycle), suggesting that these cells were undergoing more proliferation (producing more cells) than their ground control counterparts. Exposure to spaceflight also resulted in cartilage cells undergoing more cell division, less cell differentiation (maturation), and less metabolic activity compared to ground controls. This is the first time that cell cultures flown in space were shown to exhibit alterations in their normal cell cycles.

## ***Do Cells Grow Differently in Spaceflight and Affect Crew Health?***

### **Cell and Molecular Biology**

A large number of experiments with microorganisms were flown. Nearly all revealed that higher populations of cells are obtained from cultures grown under microgravity conditions than are obtained in cultures grown statically on the ground, possibly due to a more homogeneous distribution of cells. Recent studies of microbial cultures grown in space resulted in a substantial increase in virulence in the space-grown cultures when used postflight to infect mice.

The response of terrestrial life to microgravity at the molecular level is reflected in the response of many of an organism's genes when gravity is significantly reduced in the environment. Human renal (kidney) cell cultures flown on the Space Transportation System (STS)-90 (1998) mission exhibited a genetic response to microgravity that exceeded all expectations. More than 1,600 of the 10,000 genes examined in the renal cells showed a change in expression (i.e., increased or decreased production of the protein products of the genes) as a result of spaceflight. Armed with these results, investigators are now focusing on specific groups of genes and their functions to try and unravel why certain genes and metabolic pathways may be amplified or reduced due to a change in gravity.



*Human renal cortical cell culture grown on STS-90 (1998).*

### **Summary**

The Space Shuttle's unique capabilities, coupled with the unbounded curiosity, energy, and creativity of scientists and engineers, enabled huge leaps in our knowledge of how biological species, including humans, react and adapt to the near weightlessness of orbital spaceflight. Over the past 3 decades, space biologists demonstrated that gravity, and the lack thereof, affects life at cellular and molecular levels. They determined how amazingly durable and plastic biological systems can be when confronted with a strange new environment like space. Even in the Columbia Space Transportation System (STS)-107 (2003) tragedy, the survival of the small soil nematode worms and the mosses on board was an extremely stunning example of plant and microbial responses and resiliency to severe stress.

Over the past 4 decades of space biology research, our textbooks were rewritten, whole new areas of study were created, new technologies were developed for the benefit of science and society, and thousands of new



## Microgravity—A Tool to Provide New Targets for Vaccine Design

The use of spaceflight as a tool for new discoveries has piqued the interest of scientists and engineers for decades. Relatively recently, spaceflight also gained the attention of commercial entities that seek to use the unique environment of space to provide opportunities for new product design and development.

For example, Astrogenetix, Inc. was formed by Astrotech Corporation, Austin, Texas, to commercialize biotechnology products processed in the unique environment of microgravity. Astrogenetix developed capabilities to offer a turnkey platform for preflight sample preparation, flight hardware, mission planning and operations, crew training, and certification processes needed within the highly regulated and complex environment of human spaceflight.

Astrogenetix's primary research mission is to discover therapeutically relevant and commercially viable biomarkers—substances used as indicators of biologic states—in the microgravity environment of space. By applying a biotechnology model to this unique discovery process, the company finds novel biomarkers that may not be identifiable via terrestrial experimentation. Through this method, Astrogenetix expects to shorten the drug development time frame and guide relevant therapeutics agents (or diagnostics) into the clinical trial process more quickly and cost-effectively.



Astronaut John Phillips activating a Fluid Processing Apparatus containing tubes of microorganisms on STS-119 (2009).

Specifically, Astrogenetix used assays of bacterial virulence in the microscopic worm *Caenorhabditis elegans*. Bacteria, worms, and growth media were launched separated in different chambers of the Fluid Processing Apparatus, which was developed by Bioserve Space Technologies, Boulder, Colorado. Astronauts hand-cranked the hardware twice, first to initiate the experiment by mixing bacteria, worms, and growth media and at a later scheduled time to add fixative to halt the process. This was the first direct assay of bacterial virulence in space without the effects of re-entry into Earth's atmosphere and delays due to offloading the experiment from the Space Shuttle. This experimental model identified single gene deletions of both *Salmonella sp* and *Methicillin-resistant Staphylococcus aureus* for potential acceleration of vaccine-based applications. The investigative team included Timothy Hammond, Patricia Allen, Jeanne Becker, and Louis Stodieck.

scientists and engineers were educated and trained. In the words of Nobel Prize-winner Baruch Blumberg, “Like the pioneering voyages of the early European explorers to the New World, Darwin’s voyages of scientific

discovery, and the historic lunar missions by the Apollo astronauts, the Space Shuttle expanded the boundaries of biology, providing insights into the role and influence of gravity on living systems.”



# Microgravity Research in the Space Shuttle Era

Bradley Carpenter

***Cells in Space***

Neal Pellis

***Physical Sciences in Microgravity***

Bradley Carpenter

Iwan Alexander

***Commercial Ventures Take Flight***

Charles Walker

*The Space Shuttle cargo capability in the early 1980s stimulated a wave of imaginative research. Space-based microgravity research gave new insights into technologies critical to the space program, medical research, and industry.*

*NASA dedicated over 20 shuttle missions to microgravity research as a primary payload, and many more missions carried microgravity research experiments as secondary payloads. The space agency's microgravity research strived to increase understanding of the effects of gravity on biological, chemical, and physical systems. Living systems benefited as well. Cells, as they adapted to microgravity, revealed new applications in biotechnology.*

*Shuttle-era microgravity research was international in scope, with contributions from European, Japanese, and Russian investigators as well as commercial ventures. Several missions in which the Spacelab module was the primary payload were either officially sponsored by a partner agency, such as the Japanese or German space agency, or they carried a large number of research experiments developed by, or shared with, international partners. NASA and its partners established close working relationships through their experience of working together on these missions. These collaborations have carried over to operation of the International Space Station (ISS) and will provide the foundation for international cooperation in future missions to explore space.*

*Much of the Space Shuttle's legacy continues in research currently under way on the ISS—research that is building a foundation of engineering knowledge now being applied in the design of vehicle systems for NASA's next generation of exploration missions.*



## Cells in Space

**Question:** *Why fly cells in space?*

**Answer:** *It helps in space exploration and provides novel approaches to human health research on Earth.*

The NASA Biotechnology Program sponsored human and animal cell research, and many of the agency's spacecraft laboratory modules supported the cell research and development necessary for space exploration and Earth applications. The shuttle, in particular, hosted

experiments in cell biology, microbiology, and plant biology.

The rationale for studying cells in space is the same as it is on Earth. Cells can be a model for investigating various tissues, tumors, and diseases. NASA's work with cells can reveal characteristics of how terrestrial life adapts to the space environment as well as give rise to technologies and treatments that mitigate some of the problems humans experience in space exploration scenarios. Embarking on cell biology experiments in space spawned an almost revolutionary approach to accommodate cells in a

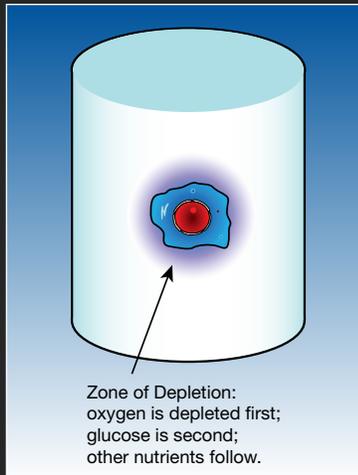
controlled culture environment. The design of equipment for propagation of cells in microgravity involved special considerations that the Earth-based cell biologist seldom accommodates.

### Unique Conditions Created by Microgravity

In microgravity, gravity-driven convection is practically nonexistent. Gravity-driven convection is familiar to us in a different context. For example, air conditioners deliver cool air through the vents above. Cooler air is more dense than warm air and gravity settles the more dense cool air closer to the floor, thereby displacing the warm air up to be reprocessed. These same convective flows feed cells on Earth-based cultures where the cooler fluid streams toward the bottom of the vessel, displacing warmer medium to the upper regions of the container. This process provides sufficient nutrient transport for the cells to thrive.

## Cell Growth in Microgravity: Going Without the Flow

In the early stages of planning for cell culture in space, scientists theorized that cells may not survive for long because of a potential inability to assimilate nutrients from the culture fluid. Although undisturbed fluid appears not to be moving, gravity-driven convection mixes the fluid. Gravity continually moves colder, more dense fluid to the bottom of the vessel, displacing the warmer fluid to the top. As the fluid on the bottom is heated, the process is repeated. In space, there is no gravity-driven convection to mix the medium and keep nutrients well distributed and available to cells. Therefore, theoretically, cells should experience a decrease in the availability of nutrients, thus slowing assimilation down to their intrinsic rate of diffusion—a rate potentially insufficient to support life. Oxygen should be the first essential to be depleted within a matter of minutes, followed by glucose. In reality, the cells do not die. Instead, they adapt to the lower rate of nutrient delivery and proceed to survive. Apparently, other more subtle convections (e.g., surface tension driven) may supply sufficient transport of nutrients. Understanding these concepts was essential to the design of cell culture systems for humans in space.



### What Happens in Microgravity?

Scientists theorized that, in microgravity, cells would rapidly assimilate nutrients from the medium and, in the absence of gravity-driven convection, the cells would consume all the nutrients around them. Nutrient transport and the mechanical sensing mechanism operate differently in the absence of gravity. NASA conducted research on the Space Shuttle over the last 2 decades of the program to elucidate the nature of cell response to microgravity and showed that, while most cell cultures can survive in microgravity, substantial adaptation is required. The outcome of this cellular research is the emergence of space cell biology as a new scientific discipline.



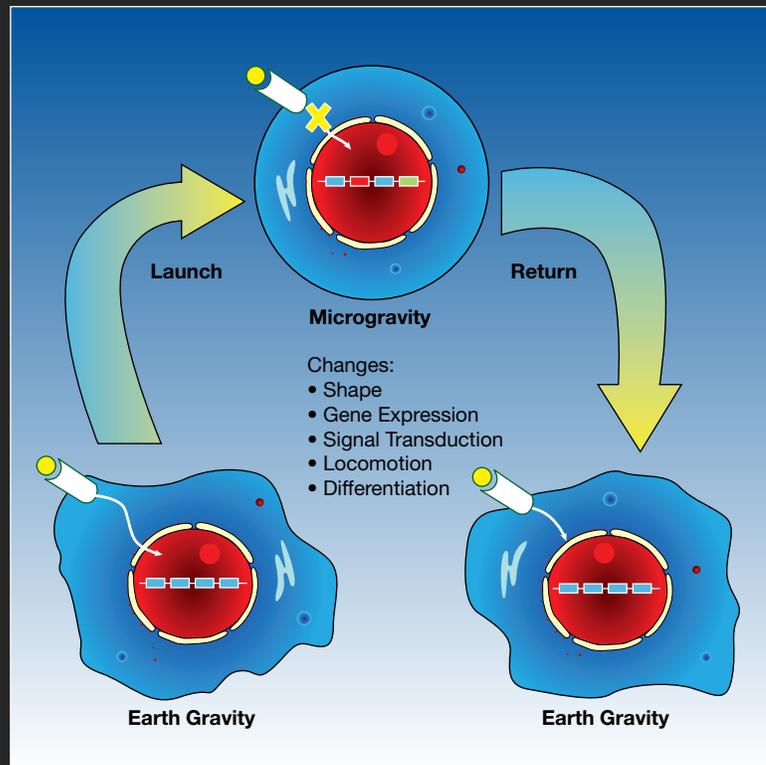
### Suite of Equipment

To meet the various requirements for a full complement of cell biology experiments, NASA developed a suite of equipment that spans from relatively simple passive cell cultures to complicated space bioreactors with automated support systems. The experiments that were supported included space cellular and molecular biology, tissue engineering, disease modeling, and biotechnology. Space cell biology includes understanding the adaptive response to microgravity in the context of metabolism, morphology, and gene expression, and how cells relate to each other and to their environment.

### Analog and Flight Research

The cell culture in space, and to a certain extent in microgravity analogs, is an environment where mammalian cells will associate with each other spontaneously, in contrast to Earth culture where cells sediment to the lower surface of the container and grows as a sheet that is one cell layer thick. In space and in an analog culture, the association results in the assembly of small tissue constructs. A construct may be made up of a single type of cell, or it may be designed to contain several types of cells. As the assembly proceeds, cells divide and undergo a process of differentiation where they specialize into functions characteristic of their tissue of origin. For example, as liver cells go through this process, they produce constructs that look and function akin to a native liver specimen. In other instances, colon cancer cells mixed with normal cells will produce assemblies that look and act like a fresh tumor biopsy.

## Transition of Cells



As cells transition to space, changes occur that provide new insights into life systems and offer the prospect of understanding the role of gravity in life as it developed on this planet. A stylized cell with its nucleus (red) containing genetic material (blocks), an example of a cell surface receptor and its communication linkage to the nucleus, and the external simulating factor (yellow ball) are displayed above in three phases: 1) on Earth at unit gravity; 2) following launch into microgravity; and 3) return to Earth. Within a few seconds after arriving in microgravity, the cell becomes round and, thereafter, a cascade of changes follows over the next few days and weeks. As the cell adapts to the new environment, it turns on some genes and turns off others. The ability to respond to certain external stimuli is diminished. This is due to a disruption (indicated by the “X”) of some cell surface receptor signal transduction pathways. In addition, cells locomote (move) very poorly in microgravity. The ability to mature and develop into functional tissues and systems seems to be favored. These observations provide a basis for robust investigation of microgravity cell biology as a means to understand terrestrial life in space and to use the space environment to foster goals in biomedical research on Earth.



These microgravity-inspired technologies are now used in cell culture and some tissue engineering studies. Scientists and physicians can produce tissues to be used as research models (e.g., cardiac tissues; cancers of the kidney, liver, colon, prostate, breast, and brain). Microgravity cultures are used in biotechnology to produce cell by-products that can be used to treat diseases and produce vaccines to prevent diseases.

### NASA Develops Special Equipment to Grow Cells—Space Bioreactor

The use of microgravity cell culture to engineer tissues from individual cells began in systems where cells were grown in a tubular vessel containing a bundle of hollow fibers that carried nutrients to the cells in the tube. As concepts for space bioreactors matured, the cylindrical rotating systems emerged because of several advantages: greater volume; a format that supported both analog culture on Earth and space cell culture; and a natural association of cells with each other rather than with the plastic or glass vessel. The system could be rendered compatible with Earth or space by setting the rotation regime to the gravitational conditions. NASA performed a validation of the first rotating bioreactor system on Space Transportation System (STS)-44 (1991). No cells were used for the validation test. Instead, scientists used small beads made of inert polymer as surrogate cells. This enabled observation of the media delivery system and movement of “cells” along flow streams in the culture fluid. Results of the experiment showed

**Mary Ellen Weber, PhD**  
Astronaut on STS-70 (1995) and STS-101 (2000).

**Colon Cancer Cells’ unique response in microgravity: reassembly and reconstruction of their tissue origin.**



*Astronaut Mary Ellen Weber with the space bioreactor on STS-70.*

*“One of my fondest memories of my shuttle missions was working preflight with the bioreactor team on its first experiment in space. I can still vividly remember my awe in watching colon cancer cells growing into cancer tissue, and the satisfaction in seeing it all come together. The experiment held so much promise early on that it was manifested on the mission well before all its details were worked out, and this gave me, its assigned crew member, the opportunity to work far more closely with these dedicated scientists than usual in getting it ready to go as well as the opportunity to learn far more about the science. Most researchers get to see their hard work come to fruition first hand, and as I watched the bioreactor successfully working in space, I was really struck—unexpectedly so—by the fact that they could not be there to witness it with me. It gave me a great sense of responsibility to do right by them, and it made me all the more proud to be a part of it.”*

characteristics consistent with maintaining live cells and set the stage for the first rotating bioreactor experiments in space.

The first investigation on the shuttle (STS-70 [1995]) used colon cancer cells as the test population to determine whether the new bioreactor system was compatible with cell assembly, growth, and maturation. The bioreactor was composed of a cylindrical culture vessel, culture medium reservoir, waste reservoir, pump (functions as a

heart), and gas exchange module that delivered oxygen and removed carbon dioxide (essentially acting as a lung). The results showed that microgravity afforded continuous suspension of the cells, spontaneous association, cell propagation, and formation of a tissue construct.

The space bioreactor facilitated rapid assembly, substantially larger constructs, and metabolically active cells. The experiment confirmed the hypothesis that microgravity facilitates



tissue morphogenesis (formation) and set the stage for use of the space environment to identify the essential stages in tissue engineering that are novel to microgravity. The ability to engineer tissue from individual cells provided tissue for research, drug testing, disease modeling and, eventually, transplantation into afflicted individuals. Subsequent colon cancer experiments on STS-85 (1997) identified some of the novel metabolic properties and demonstrated the mechanism used by the cancer to spread to other organs.

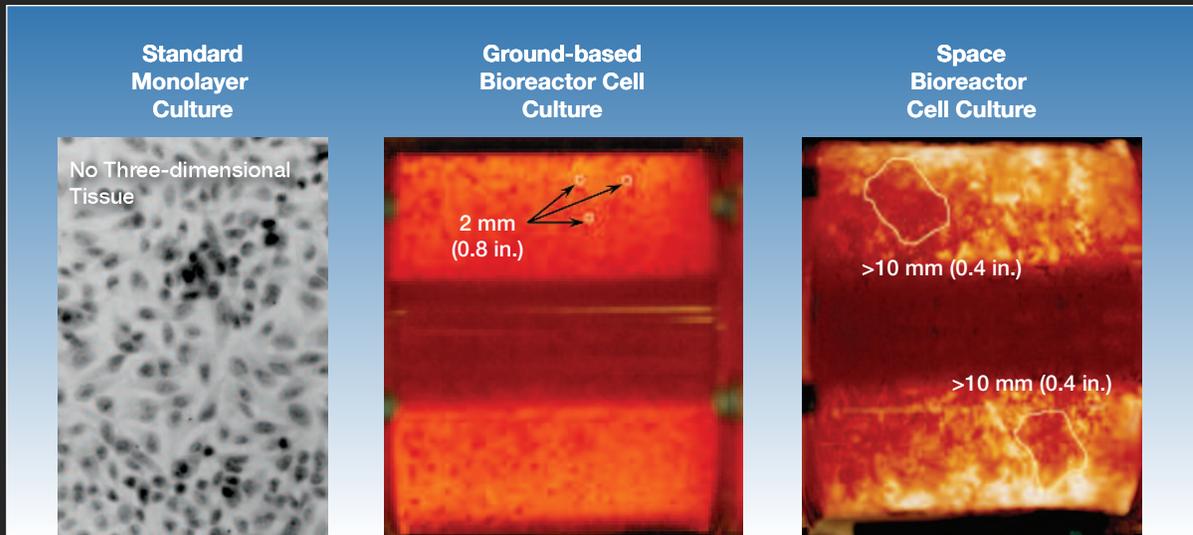
Interest in space cell culture opened the new vista of space cell biology. Mammalian cells are enclosed by a pliable lipid membrane. On Earth, those cells have a characteristic shape; however, when in microgravity, most mammalian cells become more spherical. Following this shape change, a cascade of adaptive changes occurs. Some genes are turned on while others are turned off, some receptors on the surfaces of cells cease to transduce signals to the inside, many cells cease locomotion (movement), and other cells will mature and change function spontaneously.

## Microgravity-induced Changes at the Cell Level

### Cells Adapt to Microgravity

On STS-62 (1994), NASA demonstrated that cells could grow in microgravity culture without succumbing to the lack of convective mixing of the medium. This demonstration occurred in a static culture system wherein rapidly dividing colon cancer cells and slowly dividing cartilage cells were placed in small culture vessels held at 4°C (39°F) (refrigeration temperature) until arriving in microgravity and reaching

## Colon Cancer Cell Cultures



The first experiment using living tissue in the space bioreactor developed at Johnson Space Center used human colon cancer cells to determine whether there are specific advantages to propagation of cells in space. NASA conducted this experiment on STS-70 (1995) and again on STS-85 (1997). The right panel shows the large tissue assemblies that readily formed within a few days in microgravity when compared with the ground-based bioreactor analog, where the assemblies were much smaller and less well developed. For reference, the left panel shows the same cells in standard culture on Earth, where the cells grew and attached to the petri dish in a single layer with little evidence of tissue formation. This experiment set the stage for using space cell culture to produce tissues with a greater parity to the actual tumor in situ in the patient. Furthermore, unlike the standard culture, it demonstrated the signature biochemicals associated with the disease.



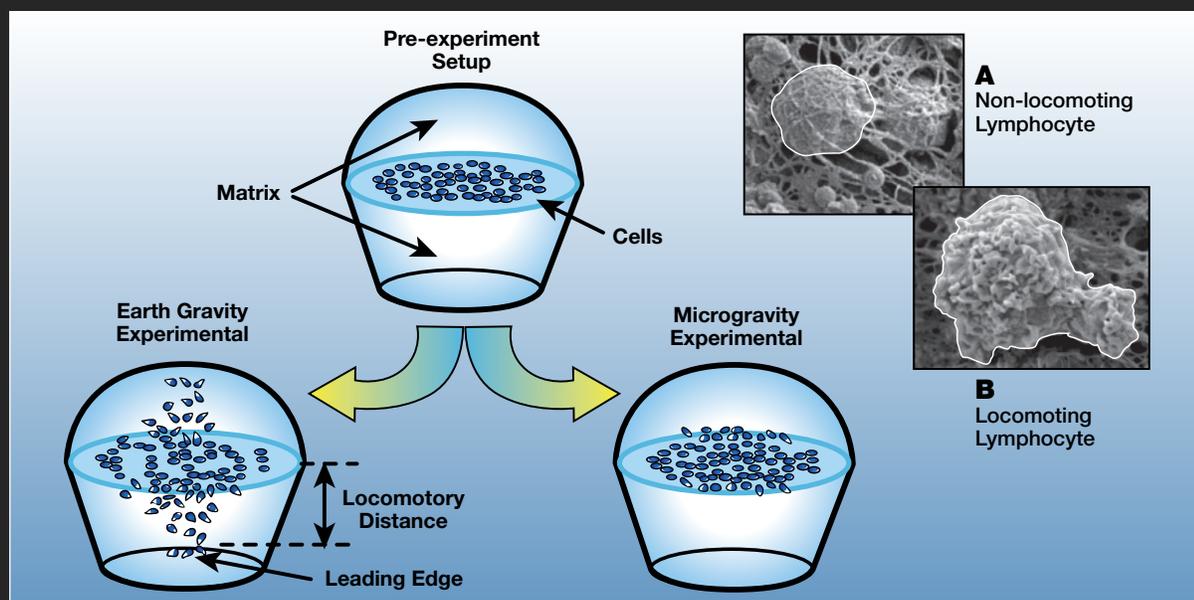
orbit where the temperature was raised to 37°C (98.6°F) (body temperature) to initiate growth. Results showed that colon cancer cells rapidly assimilated nutrients from the medium while cartilage took more than twice as long to deplete nutrients. Neither cell population succumbed to the depletion but, rather, changed their metabolic profile to adapt to more stringent

conditions. Thus, bioreactors to support these cells for long-term experiments needed to accommodate re-feeding and waste disposal to ensure health of the tissue. The results of this experiment set the requirements for final design of the space bioreactors to grow bulk culture in microgravity.

## Immune Cells Have Diminished Locomotion in Microgravity

The immune cells known as lymphocytes locomote and traverse many environments within the body to engage invading microbes and effect their destruction or inactivation. Experiments conducted on STS-54 (1993) and STS-56 (1993) were the first

## Cell Locomotion



Human immune cells (lymphocytes) locomote through tissue matrix (intercellular cement) as part of their normal function in mediating immunity. Experiments performed in the analog culture system indicated a profound loss of the ability to locomote through matrix. This experiment described above was performed on STS-54 (1993) and STS-56 (1993). The matrix material is gelled collagen cast in two separate upper and lower phases, and the interface is loaded with human lymphocytes. Some were incubated as ground controls and others were transported to the shuttle. Locomotion remained arrested throughout the preparation and transport to space by maintaining them at 4°C (39°F). Upon arrival in microgravity, the temperature was raised to 37°C (99°F) in the experimental and control specimens. The lower left control shows how the lymphocytes locomote symmetrically up and down. Distance of locomotion to the leading edge can be measured using a microscope. In space, the experimental specimens evidenced very little locomotion. Non-locomoting lymphocytes are round and incapable of deforming (photo A), whereas locomoting lymphocytes deform and extend the process toward the direction of movement (photo B). The loss of locomotion in space indicates a potential defect in immunity in space. Loss of locomotion for extended periods of time can profoundly impact immunity. Locomotion is essential to this trafficking of lymphocytes through lymphoid organs and to sites of infection or invasion by cancer cells.



to show that these important immune cells have diminished locomotion in microgravity. Lymphocytes from a total of six donors were introduced into natural matrix (collagen) and kept at 4°C (39°F) until achieving orbit, where the temperature was raised to 37°C (98.6°F). Results showed that locomotion was inhibited by more than 80% in all specimens. Locomotion is a critical function in the immune system. Cessation does not have immediate effects; however, if sustained, it can contribute to a decline in immune function in space. Preparation for long-duration (in excess of 1 year) excursions in space will require extensive research and preparation to ensure the immune system functions normally throughout the entire mission. From strictly a cell biology perspective, the experiment was a milestone demonstration that locomotion can be modulated by a physical factor (gravity) rather than a biochemical factor.

### Gene Expression Changes

Gene expression—defined as which genes are turned on and/or off in response to changing conditions—changes with almost every stimulus, stress, or alteration offered by our environment and activities. Most of these responses at the gene level occur in suites of genes that have been refined through evolution. This is why life systems can adapt to various environmental stimuli to survive and even thrive. Since all Earth organisms evolved in Earth gravity, the effect of microgravity on these genetic suites was unknown. Understanding the response at the genetic level to

microgravity will give new insights to the changes necessary for adaptation.

New technology allows for the investigation of changes in more than 10,000 genes in a single experiment. The first genetic signatures for cells in microgravity were conducted on STS-106 (2000) using human kidney cells as a test model. The results provided a provocative revelation. Out of 10,000 genes tested, more than 1,600 were significantly changed in expression. Normally, a suite of genes refined through evolution is on the order of 20 to 40 genes. The enormous response to microgravity suggests there is not a refined suite, and the response is made up of genes that are essential to adaptation—some are incidental and unrelated to adaptation, and some are consequential to the incidental activation of unnecessary genes. Analysis of gene expression showed that hypergravity (centrifugations at 3 gravitational force [*g*]) has a more refined set of about 70 genes. This is likely due to terrestrial life experiencing hypergravity during accelerations (running, starting, or stopping). On the other hand, analog microgravity culture on Earth also had a large response suite of 800 genes. Of those genes, only about 200 were shared with the microgravity suite.

The significance of these results is multifold. For short-duration missions, we will want to manage any untoward effects brought about by the response. For long-duration missions in space and permanent habitation on planetary surfaces, we will want to know whether there is a refinement in the gene suite and whether, in conjunction with the new environment, it poses the possibility for permanent changes.

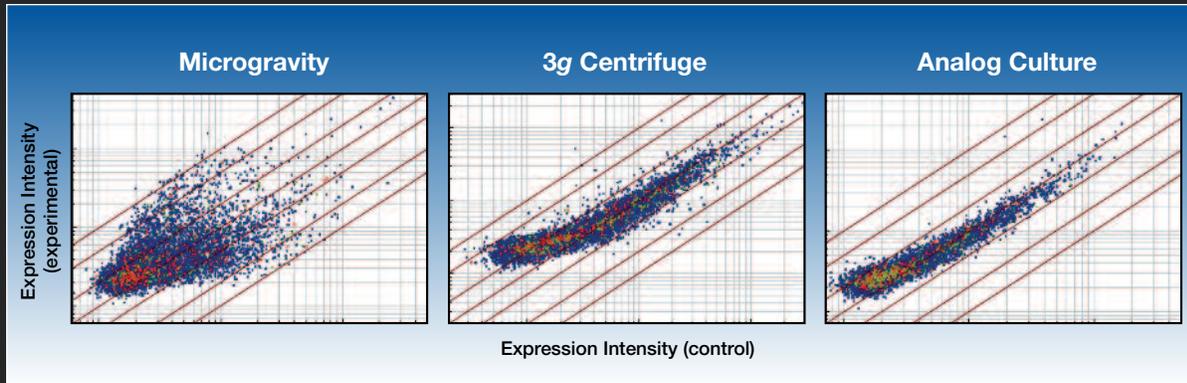
STS-105 (2001) hosted an experiment on human ovarian carcinoma, asking whether space cell culture gave a gene expression profile more like the actual tumor in the patient or like that observed in standard cell culture on Earth. Results showed tissue-like assemblies that expressed genes much in the same profile as in the tumor. This is significant because these results give scientists a more robust tool to identify specific targets for chemotherapy as well as other treatments.

Space cell culture offers a unique opportunity to observe life processes that otherwise may not be apparent. Forcing terrestrial life to muster its adaptive mechanisms to survive the new environment makes evident some new characteristic and capabilities of cells and other terrestrial life. One of the observations is the induction of differentiation (the process by which cells mature and specialize). The shuttle hosted numerous experiments that confirmed unique differentiation patterns in cancer cells from colon, ovary, and adrenals as well as human kidney cells and mouse cells that differentiate into red blood cells. All but the mouse cells were on STS-105. The mouse cell experiment was performed on STS-108 (2001).

In summary, these experiments opened a new understanding of the differentiation process and products of cells. The processes revealed aspects useful in proposing new approaches to treatment of disease and tissue engineering and to understanding complex developmental pathways. On the product side, materials were produced that may lead to new biopharmaceuticals, dietary supplements, and research tools.



## Gene Expression Differs at Three Gravity Levels



NASA performed experiments using human kidney cell cultures on STS-105 (2001) and STS-106 (2000) to investigate the gene expression response to microgravity and compare it to hypergravity and to an analog culture system on Earth. In a sample set (10,000 genes), the genes turned on and off compared with the control in normal culture on Earth. If the expression is identical in control and experimental conditions, the dots line up on the diagonal line passing through the origin. Genes that are turned on are above and beyond the first parallel diagonal line. Genes below and beyond the first parallel diagonal are decreased in expression compared with the control. In microgravity, more than 1,600 of the

10,000 genes are up-regulated or down-regulated compared with the control, meaning that it is unlikely that terrestrial life has a preformed, inherited set of genes used to adapt to microgravity. The cells were then subjected to 3 gravitational force ( $g$ ) using a centrifuge. The array is more compacted. Fewer than 70 genes are affected, suggesting that terrestrial life has a history of responding to hypergravity. The last panel shows the same cells in response to microgravity analog cell culture. More than 700 genes modified in response to the analog system that rotates the cell culture, such that the cells are falling continuously. Analysis indicated that it shared about 200 genes with that observed in microgravity.

Observations from early experiments strongly suggested that the space environment may promote conditions that favor engineering of normal tissues for research and transplantation. Experiments in ground-based analog culture suggested that microgravity can facilitate engineering of functional cartilage starting from individual cells. (Cartilage is the tissue that forms the joints between bones.) Cartilage tissue was chosen because of its low metabolic demand on the culture

system, durability, and conveniently observed characteristics of maturity and functionality. STS-79 (1996) flew a bioreactor containing beef cartilage cells to the Russian space station Mir. The culture set a landmark for 137 consecutive days of culture in microgravity. Results from this experiment and subsequent ground-based research: 1) confirmed the utility of microgravity in tissue engineering; 2) showed that generation of cartilage in microgravity produces a very

pliable product when contrasted to native cartilage; and 3) showed that on transplantation the less mature, more pliable space cartilage remodels into the recipient site much better than mature cartilage. The study suggests that microgravity and space technology are useful in developing strategies for engineering tissues from a small number of cells.



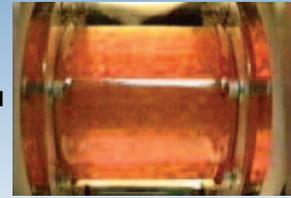
## Human Prostate Cancer Cells

On STS-107 (2003), NASA performed an experiment to investigate a model of metastatic prostate cancer. Prostate cancer is more manageable as a local disease, which is why there is such emphasis on preventive measures. Management of the disease becomes difficult when the tumor metastasizes to bone. Therein, the tumor establishes a relationship to that which contributes to its intractable state. Space cell culture offers an environment consistent with culturing two different kinds of cells harmoniously and also favors reassembly of cells into ordered tissue arrays. The upper cylinder shows the rapid assembly of the cells into tissue constructs that are much larger than those in the lower cylinder (controlled on Earth). The assemblies propagated in space achieved diameters approaching 2 cm (0.79 in.), while those on the ground were about 3 mm (0.19 in.). The result demonstrated the value of space cell culture in providing robust models for investigating human disease. These specimens were not analyzed, since they were not recovered from the ill-fated Columbia mission.

Flight



Ground



Coculture of Bone Marrow Stromal Cells and Prostate Cancer Cell Line

### Human Prostate Cancer Cells Grew Well in Microgravity

In pursuit of using space to understand disease processes, NASA conducted experiments on STS-107 (2003) to understand the special relationship between prostate cancer and bone marrow cells. Prostate cancer, like breast cancer, is a glandular tumor that is a manageable disease when treated at its origin. In contrast, when tumors spread to other areas of the body, the disease becomes intractable. The experiment on STS-107 modeled the metastatic site in the bone for prostate cancer. Results showed the largest tissue constructs grown in space and demonstrated the outcome of the cohabitation of these two cell types. It also showed that we could produce these models for research and

provide a platform for demonstrating the contribution of the normal cell environment to the establishment and maintenance of the tumor at a new site. With such a model, we may identify new targets for therapy that help prevent establishment of metastases.

### The Future of Space Cell Biology

Research in cell science plays a significant role in space exploration. Cells, from bacteria to humans, are the basic unit of all life. As is true for Earth-based biomedical research in cells, the observations must be

### Important Questions:

Does the cell respond directly to the change in gravitation force, or is it responding to conditions created by microgravity?

What does terrestrial life do to adapt and thrive in space?

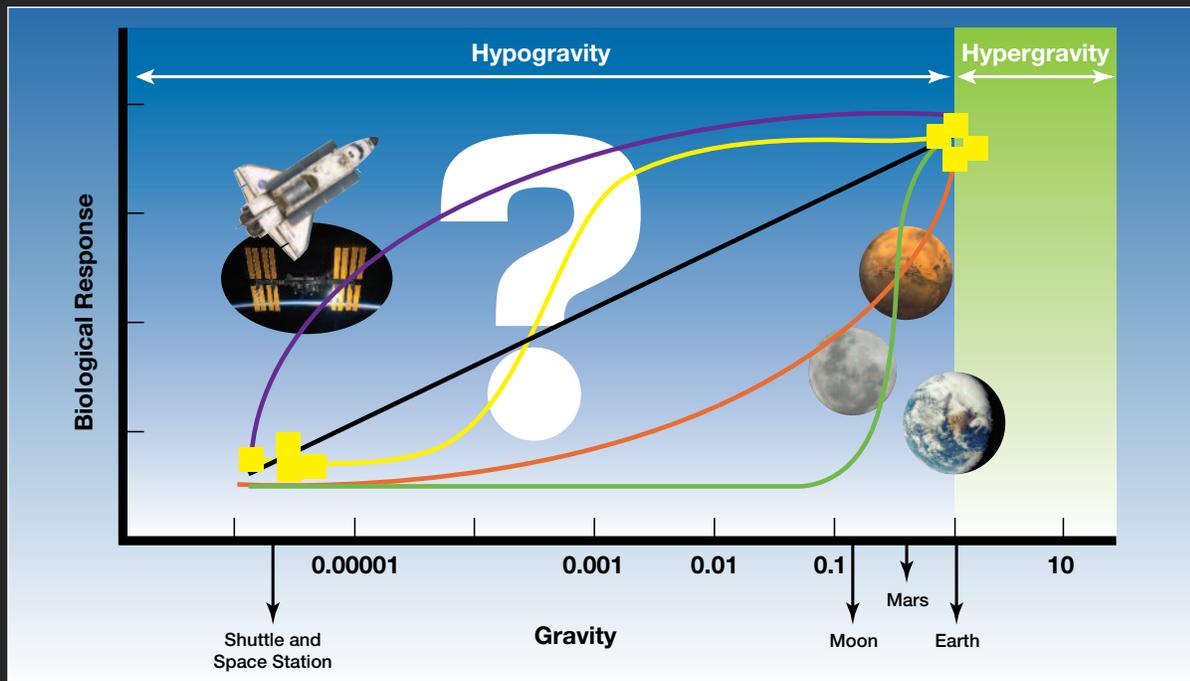
Does microgravity influence how life might evolve after many generations in space?

What is the effect of microgravity on cells from major organs and the immune and digestive systems?

How much gravity is necessary to have normal function?



## What Is the Relationship Between Gravity and Biological Responses?



The future of space cell biology includes a critical question regarding the relationship of gravity to various biological responses within the systems of the human body as well as in microbes, plants, animals, and bioprocessing systems. The possible relationships are depicted as lines on the graph, where values are known for the shuttle, space station, and Earth. The knowledge of the actual relationship will enable better understanding of human adaptability on the moon ( $1/6$  gravitational force [ $g$ ]) and Mars ( $3/8g$ ). Furthermore, it will assist in the design of artificial  $g$  technologies. Knowledge of biologic responses on Earth reveals that the response relationships to stimuli are sigmoid, as in the yellow and green curve, and that the range of the response is usually within one tenfold increment of the normal physiologic state (Earth). Thus, the green relationship may be the most likely one. With this probability, research on moon and Mars gravity becomes more important in exploration planning. Depending where on the “ $g$ ” scale the s-shaped part of the curve flexes, that is the amount of  $g$  that will begin to restore normal function.

consistent at the tissue, organ, and whole-organism level to be useful in developing treatments. Because we cannot perform experiments that may be difficult or even unethical in humans, biomedical researchers rely

on cell-based research to investigate fundamental life process, diseases, and the effects of drugs and environment on life. Thus, part of our understanding of microgravity, hypogravity (such as the level found on Mars or the moon),

radiation, and environmental factors will come from cell studies conducted in space and in analog culture systems.

The answer to the last question may have the most impact on risk reduction for humans exploring space. The answer



will not only reveal the gravity force necessary to have acceptable physiologic function (bone health, muscle conditioning, gastrointestinal performance, etc.), it also may set requirements for the design of vehicles, habitats, exercise systems, and other countermeasures. The pervasive question is: How much gravity do you need? We do not know the mathematical basis of the relationship of gravity to biologic function. The history of research in space focused on microgravity (one millionth of Earth gravity) and, of course, there is a wealth of data on biologic function on Earth. Given these two sets of data, at least four different relationships can be envisioned. Of the four, the sigmoid (s-shaped) relationship is the most likely. The likely level for biological systems will be around  $1/10g$ . Since the moon and Mars are  $1/6$  and  $3/8g$ , respectively, it will be critically important that scientists have an opportunity to determine biological response levels and begin to conduct the mathematical relationship between  $g$  and biological function.

As NASA proceeds toward a phase of intensified use of the International Space Station (ISS) for research, it is important to have a robust plan that will continue the foundational research conducted on the shuttle and procure the answers that will reduce health risks to future spacefarers. When the United States enacted the national laboratory status of the ISS, it set the stage for all federal agencies to use the microgravity environment for their research. Increasing the science content of orbiting facilities will bring answers that will enable reduction of risks to explorers and help ensure mission success.

## **Physical Sciences in Microgravity**

### **What is Gravity?**

Gravity is a difficult thing to escape. It also turns out to be a difficult thing to explain. We all know enough to say that things fall because of gravity, but we don't have easy answers for how gravity works; i.e., how the mass of one object attracts the mass of another, or why the property that gives matter a gravitational attraction (gravitational mass) is apparently the same property that gives it momentum (inertial mass) when in motion. Gravity is a fundamental force in physics, but how gravity is bound to matter and how gravitational fields propagate in space and time are among the biggest questions in physics.

Regardless of how gravity works, it's clear that Earth's gravity field cannot be easily escaped—not even from a couple hundred miles from our planet's surface. If you stepped into a hypothetical space elevator and traveled to the 100,000th floor, you would weigh almost as much as you do on Earth's surface. That's because the force that the Earth exerts on your body decreases at a rate inversely proportional to twice your distance from the center of the Earth. In an orbit around the Earth, the force exerted by our planet's mass on a spacecraft and its contents keeps them continually falling toward the Earth with an acceleration inversely proportional to the square of the distance from the center of the planet. That's Newton's law of gravitation.

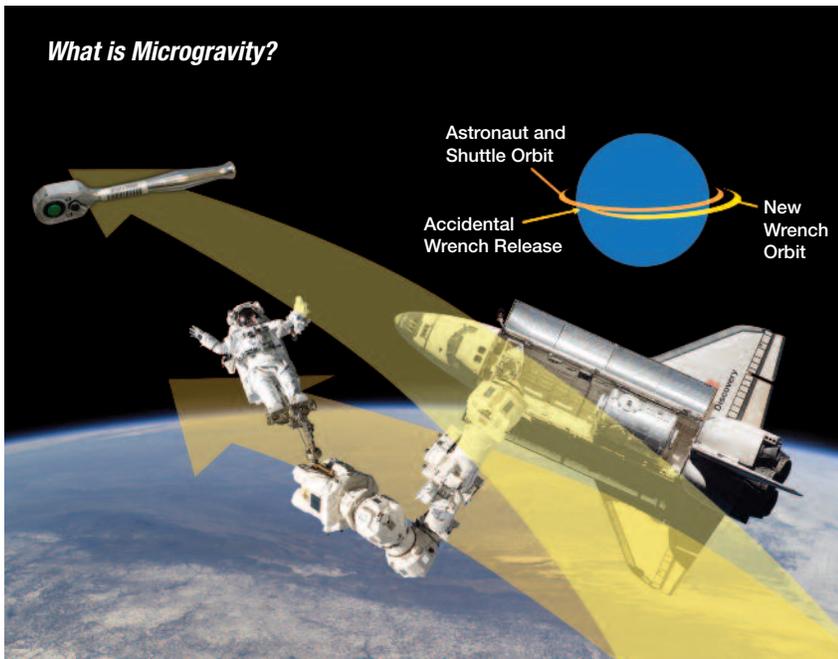
Gravity certainly works on and in airplanes. When you are traveling in an airplane during a steady flight, gravity keeps you firmly in your seat.

The lift created by air flowing around the wings keeps an airplane and your seat aloft under you—and that's a good thing. Now imagine being in an airplane that has somehow turned off its lift. In this scenario, you would fall as fast as the airplane was falling. With your seat falling out from under you at the same rate, the seat would no longer feel your weight. No force would be holding you in it. In fact, you would be approximately weightless for a short period of time.

### **Weightlessness in Space**

The essence of conquering gravity and sustaining weightlessness for longer than a few seconds is velocity. A spacecraft has to be moving very fast to continually fall toward Earth but still stay in space. Reaching that speed of a little over 27,500 km (17,000 miles) per hour provides a lot of the excitement of spaceflight. It takes a great deal of energy to put an object into Earth orbit, and that energy goes primarily into attaining orbital velocity. An astronaut in Earth orbit has kinetic energy equivalent to the explosion of around 454 kg (1,000 pounds) of TNT. Once an astronaut reaches orbital velocity, he or she is a long way toward the velocity needed to escape Earth's gravity, which is 1.4 times orbital velocity.

When you're in a vehicle moving fast enough to fall continually toward the Earth, it doesn't look or feel like you're falling. At least, not the kind of falling that people are accustomed to—the kind that ends in a painful collision with the ground. You have the feeling of being light, and the things around you are light, too. In fact, everything floats if not fastened to something. Items in the spacecraft are falling with



*Imagine an astronaut tethered to the outside of the shuttle. The astronaut and the shuttle are in orbit together. If the astronaut releases a tool, the tool generally goes into a slightly different orbit because it has to maintain a different speed to achieve the same orbit as the shuttle. The astronaut, shuttle, and tool are in orbit with their outward acceleration from the Earth, balanced by Earth's gravity. The slight differences in orbit make it seem, to the astronaut, that a small acceleration is pushing the wrench away. This is microgravity.*

you. With everything accelerating toward Earth at precisely the same rate within this falling frame of reference, Earth's gravity is not apparent. To an outside observer, gravity is still obvious—it's the reason you're in an orbit and not flying away from Earth in a line to space.

### Early Low-gravity Technology

The consequences of being weightless were merely hypothetical until the dawn of space travel, with one small exception: One hundred years prior to the launch of the first rocket beyond Earth's atmosphere, spherical lead shot was manufactured by allowing molten lead to solidify in free fall inside a shot tower. As long as the shot wasn't

falling fast enough for air resistance to deform it, the absence of gravitationally created hydrostatic pressure in the falling lead drop that allowed it to assume a spherical shape as the liquid was driven by thermodynamics into a volume of minimum exposed surface. The falling shot quickly hardened as it cooled, and it collected in a water bath at the bottom of the tower. The shot-manufacturing industry relied on this early low-gravity technology until the first decade of the 20th century.

### Physics Environment in Space

Spaceflight provides a good place to conduct experiments in physics—experiments that would not be possible on Earth. Wernher von Braun (center

director at Marshall Space Flight Center from 1960 to 1970) had more practical applications, such as making ball bearings in space. Several simple experiments were flown on Apollo 14 and performed by the crew on the return from the moon. More experiments were conducted on the three Skylab missions—an early space station built in the 1970s—with promising results reported in areas such as semiconductor crystal growth. By the time of Skylab, however, the next era of space exploration was on the horizon with the approval of the Space Shuttle Program in 1972.

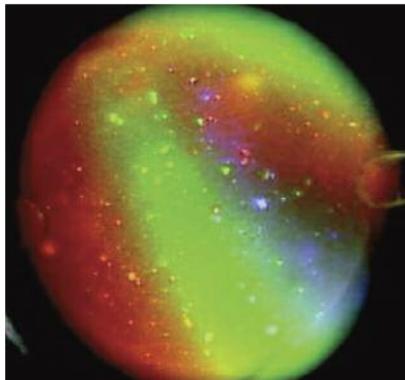
### Fundamental Physics

One of the great questions of physics is the origin of long-range order in systems of many interacting particles. The concept of order among particles is a broad one—from simple measures of order, such as the density of a collection of molecules or the net magnetization of the atomic nuclei in an iron bar, to complex patterns formed by solidifying alloys, turbulent fluids, or even people milling about on an urban sidewalk. In each of these systems, the “particles” involved interact nearly exclusively with only their near neighbors; however, it's a common observation in nature that systems composed of many interacting elements display ordering or coherent structures over length scales much larger than the lengths describing the particles or the forces that act between them. The term for the distinctive large-scale behavior that results from cooperatively interacting constituent particles is “emergent phenomena.” Emergent phenomena are of interest to science because they appear to be present at virtually every scale of the natural world—from the microscopic to the



galactic—and they suggest that common principles underlie many different complex natural phenomena.

Phase transitions at a critical point provide physicists with a well-controlled model of an emergent phenomenon. Pure materials, as determined by thermodynamics, exist in a particular state (a “phase”) that is a function only of temperature and pressure. At a point called a “critical point,” simple single-phase behavior breaks down and collective fluctuations sweep through the system at all length scales—at least in theory. The leading theory that has been developed to describe emergent phenomena, such as critical point fluctuations, is called “renormalization group theory.” It provides a model that explains how the behavior of a system near a critical point is similar over a large range of scales because the physical details of many interacting molecules appear to average out over those scales as a result of

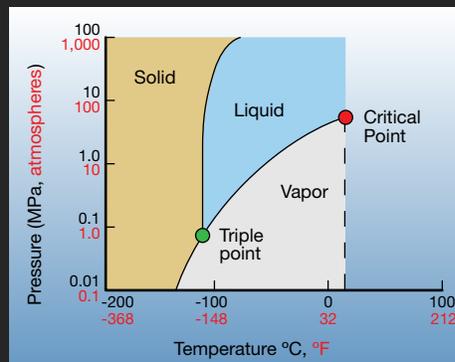


*Small particles in a colloidal solution assemble to form an ordered crystalline structure, such as the opalescent crystalline particles shown in this image taken on STS-73 (1995). Building an understanding of emergent phenomena remains one of the great challenges of physics. Explaining the origins of long-range order and structures in complex systems is key to advancing potential breakthroughs, and the experiments in fundamental physics aboard the shuttle played a significant role.*

## Critical Point Experiments Test Theories

The critical point of xenon is 289 K, 5.8 MPa—or 15.85°C (60.53°F), 57.2 atm. Note that the axis on the left is logarithmic. Research on STS-52 (1992) measured the phase boundary between normal liquid helium and superfluid helium. (Superfluids, such as supercooled helium-4, exhibit many unusual properties. The superfluid component has zero viscosity, zero entropy, and infinite thermal conductivity.) This shuttle research confirmed the renormalization group theory better than any Earth research. These types of research questions are now being studied on the International Space Station.

*NASA tested the theory for gas-liquid critical phenomena on STS-97 (1997).*



*The Lambda Point Experiment cryostat assembly (identified by the JPL insignia) in the STS-52 (1992) payload bay.*



cooperative behavior. Renormalization group theory is one of the great developments of physics during the 20th century. The most precise tests of this theory's predictions for critical point phenomena relied on experiments carried aboard the shuttle.

Careful critical point experiments required the ultimate in precise control of pressure and temperature to the extent that the difference in pressure, caused by gravity, between the top and the bottom of a small fluid sample in a laboratory on Earth by the mid 1970s became the limiting factor in experimental tests of renormalization group theory.

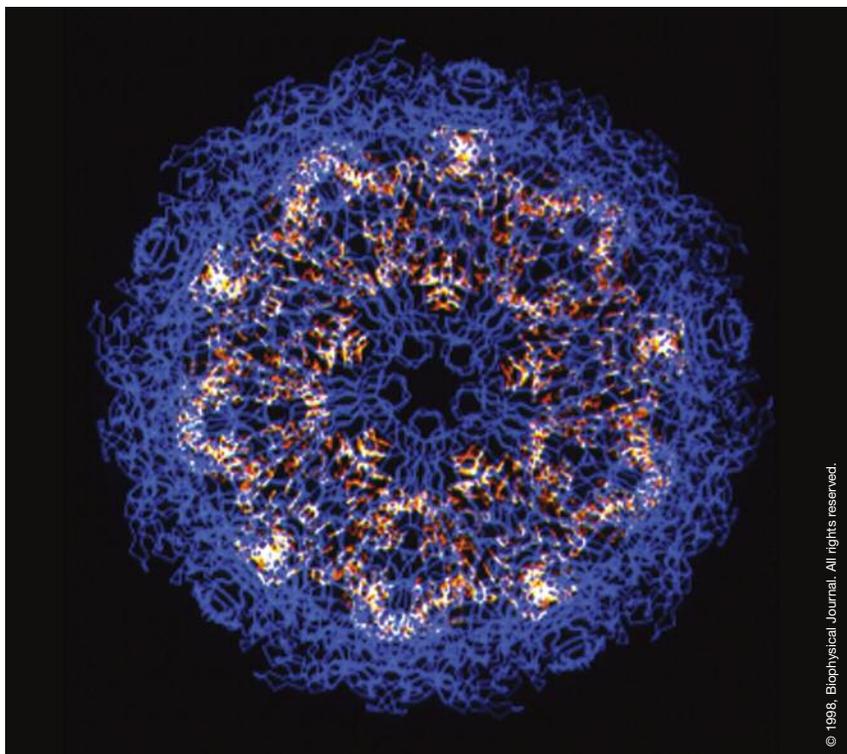
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## Protein Crystal Growth

A foundation for the explosion of knowledge in biological science over the past 50 years has been the understanding of the structure of molecules involved in biological functions. The most powerful tool for determining the structure of large biomolecules, such as proteins and DNA, is x-ray crystallography. In traditional x-ray crystallography, an x-ray beam is aimed at a crystal made of the molecule of interest. X-rays

impacting the crystal are diffracted by the electron densities of each atom of each molecule arranged in a highly ordered crystal array. Because nearly each atom of each molecule is in a highly ordered and symmetrical crystal, the x-ray diffraction pattern with a good crystal is also highly ordered and contains information that can be used to determine the structure of the molecule. Obtaining high-quality protein crystals has been a critical step in determining a protein's three-dimensional structure since the time when Max Perutz first used x-ray crystallography to determine the structure of hemoglobin in 1959. A few proteins are easily crystallized. Most require laborious trial-and-error experimentation.

The first step in growing protein crystals is preparation of as pure a protein sample as can be obtained in quantity. This step was made easier for many molecules in recent years with the ability to increase the products of individual genes through gene amplification techniques; however, every purification step is still a tradeoff with loss of starting material and the likelihood that some of the molecules in solution will denature or permanently change their shape, effectively becoming contaminants to the native molecules. After biochemists have a reasonably pure sample in hand, they turn to crystal-growing recipes that vary many parameters and hunt for a combination that will produce suitable crystals. Although usable crystals can



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*This molecular structure of the Satellite Tobacco Mosaic Virus was captured at 1.8-angstrom (0.18-nanometer) resolution from analysis of crystals obtained on experiments performed on the International Microgravity Laboratory-2 mission (STS-65) in 1994. The best of these crystals was 30 times larger and produced 237% more data than any previous Earth-grown crystals and yielded what was, at that time, the highest-resolution structure of a virus ever obtained.*



be as small as 0.1 mm (0.004 in.) on a side, the crystals often take weeks or even months to grow, so biochemists will normally try many combinations simultaneously and in specially designed trays. It is not unusual to spend several years finding good growth conditions for a protein.

### **Effects of Gravity on Protein Crystal Growth**

Gravity has two principal effects in protein crystal growth. The first is to cause crystals to sink to the bottom of the solution in which they are growing. As a result, the growing crystals can pile up on each other and fuse, thus becoming a single mass that can't be used for data collection. The second effect of gravity is to produce weak but detectible liquid flow near the surface of the growing crystals. Having contributed some of its dissolved protein to the growing crystal, liquid near the crystal surface is lighter than liquid farther away. Due to gravity, the lighter liquid will rise. The consequences of this flow for crystal quality are complex and even now not fully understood. At the beginning of the shuttle era, German chemist Walter Littke thought that liquid flow near the growth surface would interfere with the molecules on the surface finding their places in a crystal. Before the first launch of the shuttle, he conducted several promising short rocket-launched experiments in which several minutes of low gravity were achieved in a suborbital flight.

### **Protein Crystallization on the Shuttle**

The first protein crystallization experiments on the shuttle were conducted in a simple handheld device carried aboard in an astronaut's kit. Encouraging results from Professor

#### **Eugene Trinh, PhD**

*Payload Specialist and NASA expert in microgravity sciences on STS-50 (1992) US Microgravity Laboratory-1 Spacelab mission.*

*"The Space Shuttle gave scientists, for the first time, an opportunity to use the space environment as an experimental tool to rigorously probe the details of physical processes influenced by gravity to gather better theoretical insight*

*and more accurate experimental data. This precious new information could not have been otherwise obtained. It furthered our fundamental understanding of nature and refined our practical earthbound industrial processes."*



*Eugene Trinh, PhD, a payload specialist for this mission, is working at the Drop Physics Module using the glove box inside the first US Microgravity Laboratory science module on STS-50.*

Littke's experiment aboard STS-61A, the D-1 Spacelab mission (1985), where he reported achieving crystal volumes as much as 1,000 times larger than comparable Earth-based controls, opened a huge level of interest including many international and commercial investigators. Professor Charlie Bugg of the University of Alabama, Birmingham, working with Professor Larry DeLucas, who went on to fly on the US Microgravity Laboratory-1 mission (1992) as a payload specialist, eventually developed a community of nearly 100 investigators interested in flying proteins.

Some investigators obtained crystals that gave spectacular results, including the highest resolutions ever attained at the time for the structure of a virus and, in several instances, the first crystals suitable for structural analysis. Other proteins, however, seemed to show no benefit from space crystallization. A major focus of NASA's research was to explain this wide range of results.

### **Modeling Protein Crystal Growth**

Physicists and biochemists constructed models of protein crystal growth processes to understand why some proteins produced better crystals in microgravity while others did not, and why crystals sometimes started growing well but later stopped. Investigators applied techniques like atomic force microscopy to examine the events involved in the formation of crystalline arrays by large and rather floppy protein molecules. The role of impurities in crystal growth and crystal quality was first documented through the work of Professor Alexander McPherson (University of California, Irvine), Professor Peter Vekilov (University of Houston, Texas), and Professor Robert Thorne (Cornell University, Ithaca, New York), along with many others. A simplified picture of a popular model is that proteins that grow better crystals in microgravity have small levels of contaminants in



solution that preferentially adhere to the growing surface and slow the growth of the molecule-high step layers that form the crystal.

Accelerated transport of contaminant species due to buoyant flow on Earth will increase the population of contaminant species on the surface, eventually inducing the formation of defects. Such proteins will produce better crystals in microgravity because strongly adhering contaminants are transported by slower molecular diffusion rather than convection, and their surface concentration on the crystal remains lower.

This research has given a detailed scientific foundation to the art and technology of protein crystallization, thus providing structural biologists with a mechanistic understanding of one of their principal tools.

## Biotechnology and Electrophoresis

In the 1970s and early 1980s, the biotechnology industry identified a large number of biological molecules with potential medical and research value. The industry discovered, however, that the difficulty of separating molecules of interest from the thousands of other molecules inside cells was a barrier to the production of therapeutic materials.

Separation techniques for biological molecules rely on using small differences between molecules to spatially separate the components of a mixture. The mobility differences that separation methods use can result from the size of the molecule, substrates to which the molecule binds, or charge on the molecule in solution.

Separation methods relying on the interaction of biological molecules

with an applied electric field, including zone electrophoresis and isoelectric focusing, use the charge on a molecule that is dependent on the solution properties (pH, ionic strength, etc.) around the molecule to separate mixtures of molecules. The throughput and resolution of these techniques are limited by the flow induced in the solution containing the molecules, heat generated by the electric current passing through the liquid, and sedimentation of the large molecules during the necessary long separations. It was recognized that electrophoresis, one of the earliest candidates for space experiments, would solve the problem of the disruptive heat-driven flows by minimizing the effect of gravity. Warmer, lighter liquid wouldn't rise in the electrophoresis cell, and device performance might be dramatically improved.

Professor Milan Bier (University of Arizona, Tucson)—a pioneer in biological separations whose discoveries did much to establish electrophoresis as a laboratory tool—conducted several important flight experiments with NASA. As Professor Bier's work on the Isoelectric Focusing Experiment proceeded and flew on several early shuttle missions, he came to understand the impact of gravitational effects on Earth-based electrophoresis. He developed designs for electrophoresis equipment that minimized the impact of gravity. Within a few years, these designs became the industry standard and a basic tool of the biotechnology industry. Commercial organizations became interested in the potential of space-based bioseparations. McDonnell Douglas Astronautics Company sponsored seven flights of a large electrophoresis device—

the Continuous Flow Electrophoresis System. Several flights included a McDonnell Douglas Astronautics Company technical expert who traveled on board as a payload specialist.

Using this facility on the shuttle middeck, Robert Snyder of the Marshall Space Flight Center, along with his colleagues, discovered a new mode of fluid behavior—electrohydrodynamic instability—that would limit the performance of electrophoresis devices even after the distortion of gravity was eliminated. The discovery of this instability in space experiments and subsequent confirmation by mathematical analysis allowed electrophoresis practitioners on Earth to refine their formulations of electrophoresis liquids to minimize the consequences of electrohydrodynamic effects on their separations. This led to experiments, conducted in a French-built facility by French pharmaceutical company Roussel-Uclaf SA, Paris.

The opportunity to conduct sequential experiments of increasing complexity was one of the benefits of these shuttle microgravity missions. Interest shown by these commercial and international organizations initiated in early shuttle missions continues today on the International Space Station (ISS).

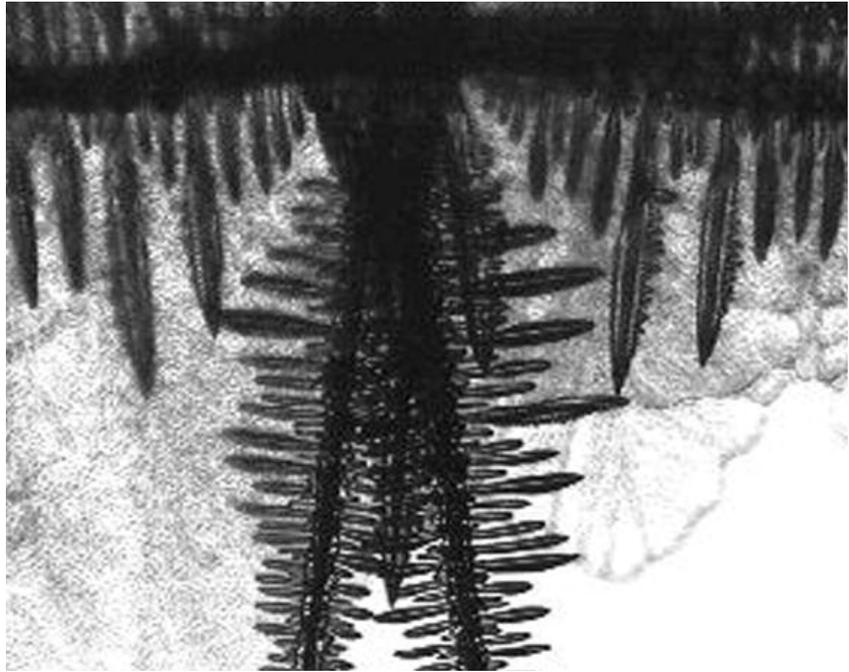
## Materials Processing and Materials Science

The semiconductor industry grew up with the space program. The progression from commercial transistors appearing in the 1950s to the first integrated circuits in the 1960s and the first microprocessors in the 1970s was paralleled, enabled, and driven by the demanding requirements of space vehicles for lightweight, robust, efficient electronics.



Since the beginning of semiconductor technology, a critical issue has been the production of semiconductor crystals from which devices can be fabricated. As device technology advanced, more stringent device performance and manufacturing requirements on crystal size, homogeneity, and defect density demanded advances in crystal growth technology. In the production of semiconductor crystals, when molten semiconductor freezes to form a crystalline solid, variations in the temperature and composition of the liquid produce density variations that cause flows as less-dense fluid rises. These flows can cause poor distribution of the components of the molten material, leading to nonuniformities and crystal defects. Studying semiconductor crystal growth in low gravity, where buoyancy-driven flows would be extremely weak, would give insight into other factors at work in crystal growth. There was also hope that in microgravity, quiescent conditions could be attained in which crystallization would be “diffusion controlled” (i.e., controlled by stable, predictable mechanisms proportional to simple gradients of temperature and composition) and that, under these conditions, material of higher quality than was attainable on Earth would be produced.

In the early 1970s, semiconductor crystal growth was one of the first concepts identified by the National Research Council for materials processing in space. Promising early results, especially on Skylab, spurred plans for semiconductor research on the shuttle. Materials processing and semiconductor crystal growth experiments were also a prominent part



*Solidification of a liquid is an unstable process under many conditions. An initially flat boundary will evolve into an elaborate web of branched dendrites. In metals, the properties of the resulting solid are highly dependent on the structure formed during solidification, making the understanding of interface evolution an important goal of materials science.*

of Soviet microgravity research. Crystal growth in space was a challenge because of the power needed by the furnaces and the containment required to meet NASA safety standards. Eventually, however, furnaces were built and flown on the shuttle not only by NASA but also by the European Space Agency and the space agencies of Japan, Germany, and France. Large furnaces flew on pallets in the cargo bay and in Spacelab while small furnaces flew on the shuttle middeck. To quantify the role of gravity in semiconductor crystal growth, NASA supported a comprehensive program of experiments and mathematical modeling to build an understanding of the physical processes involved in semiconductor crystal growth.

The results of materials processing and materials science experiments strongly influenced scientific understanding in several technologically important areas:

- Control of homogeneity and structural defects in semiconductor crystals
- Control of conditions for production of industrial alloys in processes like sintering and precipitation hardening
- Measurement of accurate thermophysical properties, such as surface tension, viscosities, and diffusivities, required for accurate process modeling

Liquid phase sintering experiments performed in low gravity yielded the unexpected results that the shape

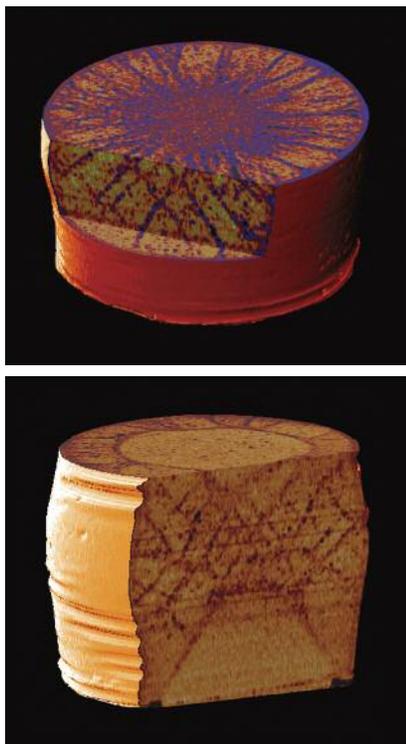


distortion of samples processed in microgravity is considerably greater than that of terrestrially processed samples. Sintering is a method for making objects from powder by heating the material in a sintering furnace below the material's melting point (solid state sintering) until its particles adhere to each other. Sintering is traditionally used to manufacture ceramic objects and has also found uses in fields such as powder metallurgy. This result led to improved understanding of the underlying causes of the shape changes of powder compacts during liquid-phase sintering with significant impact on a \$1.8 billion/year industry.

Space experiments on the prediction and control of microstructure in solidifying alloys advanced theories of dendritic (from *dendron*, the Greek word for tree) growth and yielded important contributions to the understanding of the evolution of solid-liquid interface morphologies and the consequences for internal structure of the solid material. Introductions to metallurgy traditionally begin with a triangle made of three interconnected concepts: process, structure, and properties. According to this triangle, the study of metallurgy concerns how processing determines structure for various metals and alloys and also determines properties. A solidifying metal develops a characteristic structure on several distinct interacting length scales. The microstructure (usually on the scale of tens of microns) is formed by the typically dendritic pattern of growth of the solid interface. The macroscale pattern of a whole casting is determined by, among other things, the distribution of solutes rejected from the solid, shrinkage of

the solid during freezing, and thermal conditions applied to the metal. The formation of structures during the solidification of practical systems is further complicated by the multiplicity of liquid and solid phases that are possible in alloys of multiple elements.

Understanding the processes that control the growth of dendrites on a growing solid is a foundation for how processing conditions determine the internal structure of a metal. Gravity can have a visible influence on the growth of dendrites because of the disruptive effects of flow caused by temperature gradients near the dendrite. Therefore, removing the effects of gravity was



*These two samples show fracture patterns in sand at two different low confining pressures. The confining pressure is an equal, all-sided pressure that is experienced, for example, by rock at some depth in the Earth. Very low confining pressures are not obtainable on Earth due to gravity.*

essential to obtain benchmark data on the growth rates, shapes, and branching behavior. In the 1990s, a series of experiments designed by Professor Martin Glicksman, then at the Rensselaer Polytechnic Institute, Troy, New York, was conducted on shuttle missions using an instrument named the Isothermal Dendritic Growth Experiment. The experiments carefully measured the characteristics of single growing dendrites in an optically transparent liquid; accurately determined the relationship among temperature, growth rate, and tip shape; and established the importance of long-range interactions between dendrites. Data from those experiments are widely used by scientists who work to improve the physical understanding and mathematical models of pattern formation in solidification.

We learned the underlying physics of freckle formation (a defect in the formation alloy that changes its physical characteristics) from early results of materials research. It was shown that convection was directly responsible for the formation of freckles, and that rotating the sample can suppress freckle formation.

The contributions of the materials effort led to many innovations in crystal growth and solidification technology, including the use of magnetic fields, rotating crucibles, and temperature-control techniques. In addition, the analytical tools developed to understand the results of space experiments were a major contribution to the use of computational modeling as a tool for growth process control in manufacturing.



## Fluid Behavior Changes in Space

Many people connect the concept of liquids in space with the familiar image of an astronaut playing with a wiggly sphere of orange juice. And, yes, liquids in space are fun and surprising. But, because many space systems that use liquids—from propulsion and thermal management to life support—involve aspects of spaceflight where surprises are not a very good idea, understanding the behavior of liquids in space became a well-established branch of fluid engineering.

The design of space vehicles—fluid and thermal management systems, in particular—made low gravity a practical concern for engineers. Decades before the space program began, airplane

designers had to create fuel systems that would perform even if the plane were upside down or in free fall. Rocket and satellite designers, however, had to create systems that would operate without the friendly hand of gravity to put liquids at the bottom of a tank, let bubbles rise to the top of a liquid, and cool hot electronic equipment with the natural flow of rising hot air.

Without gravity, liquid fuel distributes itself in a way that minimizes its total free energy. For most fuels, liquid at the surface of the tank has a lower energy than the liquid itself, which means the fuel spreads out to wet the solid surfaces inside the tank. When bubbles are created in a fluid in space, in the absence of other factors the bubbles will sit where they are. Buoyancy,

which causes bubbles to rise in liquids or hot air to rise around a flame, is the result of gravity producing a force proportional to density within a fluid. Many aspects of a vehicle design, such as its mechanical structure, are driven primarily by the large forces experienced during launch. For fluid and thermal systems, low gravity becomes a design driver.

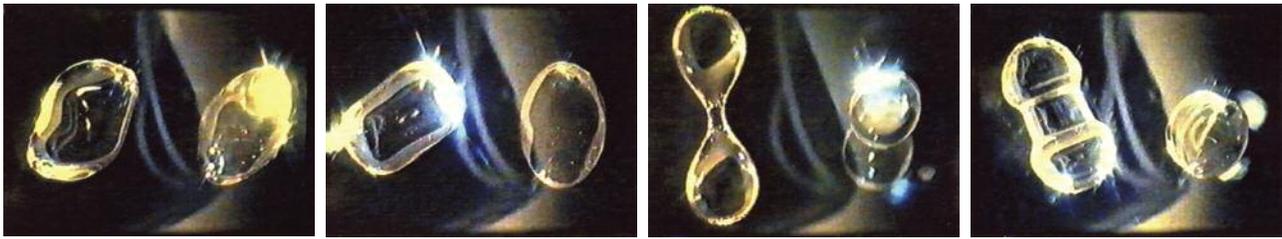
A great deal of low gravity research performed in the 1960s focused on making liquid systems in space reliable. Low gravity experiments were performed by dropping the experiment from a tower or down a deep shaft or flying it in an aircraft on a parabolic trajectory that allowed the experiment to fall freely for about 20 seconds. The experiments possible in drop shafts and aircraft didn't allow enough time to test many technologies. As a result, engineers weren't sure how some familiar technologies would work in the space environment.

Low-gravity fluid engineering began with Apollo-era research focused on controlling liquid fuels; i.e., making sure liquid fuels didn't float around inside their tanks like an astronaut's orange juice. NASA performed most of this research in drop facilities, where experiments conducted in up to 5 seconds of free fall allowed basic ideas about fluid management to be investigated.

The arrival of the Space Shuttle opened the window for experiment duration from seconds to days and inspired the imaginations of scientists and engineers to explore new areas.



*Astronauts Kathryn Thornton and Kenneth Bowersox observe a liquid drop's activity at the Drop Physics Module in the science module aboard the Earth-orbiting Space Shuttle Columbia (STS-73 [1995]). The two were joined by three other NASA astronauts and two guest researchers for almost 16 days of in-orbit research in support of the US Microgravity Laboratory mission.*



*Drop physics experiments using advanced noncontact manipulating techniques on US Microgravity Laboratory (USML)-1 and USML-2 (STS-50 [1992] and STS-65 [1994], respectively) helped scientists understand the complex physical mechanisms underlying the seemingly simple processes of droplet shaping, splitting, and fusion.*

The source of engineering problems with liquids in space is the partially filled container, or the gas-liquid interface. Without gravity, surface tension—the force that pulls a liquid drop into a sphere—together with the attraction of the liquid to the solid surfaces of the container determine the shape that a liquid will assume in a partially filled container.

To understand the unique behavior of liquids in space, researchers needed to look at the critical pieces of information in the liquid boundaries. Fluid physics experiments in the Spacelab Program, such as the Surface Tension-Driven Convection Experiment developed for Professor Simon Ostrach of Case Western Reserve University, Cleveland, Ohio, and the Drop Physics Module developed for Professors Robert Apfel of Yale University, New Haven, Connecticut, and Taylor Wang of Vanderbilt University, Nashville, Tennessee, led a wave of research into the properties of liquid interfaces and their roles in fluid motions. This research contributed to advances in other areas, such as microfluidics, in which the properties of liquid interfaces are important.

The shuttle enabled researchers to explore many new kinds of fluid behavior. Two examples out of many include: the Mechanics of Granular Materials experiment, and the Geophysical Fluid Flow Cell experiment. The Mechanics of Granular Materials experiment, developed by Professor Stein Sture at the University of Colorado,

Boulder, examined the fluid-like behavior of loosely compressed soils and helped in understanding when and how, in situations like earthquakes, soils abruptly lose their load-bearing capability. Data from the experiment will also help engineers predict the performance of soils in future habitat foundations and roads on the moon, Mars, and other extraterrestrial



*One of the earliest concerns about fluid behavior in microgravity was the management of propellants in spacecraft tanks as they orbited the Earth. On the ground, gravity pulls a fluid to a bottom of a tank (Earth environment, left). In orbit, fluid behavior depends on surface tension, viscosity, wetting effects with the container wall, and other factors. In some cases, a propellant can wet a tank and leave large gas bubbles in the center (microgravity, right). Similar problems can affect much smaller experiments using fluids in small spaces.*



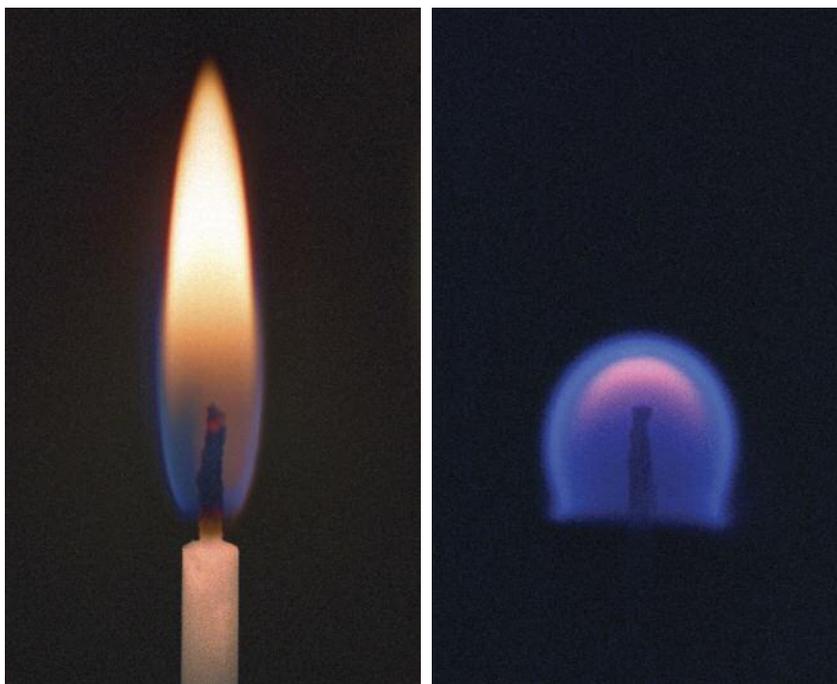
applications where the weight of the soil is much lower than on Earth.

The Geophysical Fluid Flow Cell experiment, developed by Professor John Hart at the University of Colorado, Boulder, used the microgravity environment to create a unique model of the internal motion in stars and gaseous planets, with a device that used an electric field to simulate gravity in a spherical geometry. The Geophysical Fluid Flow Cell flew on Spacelab 3 (1985), and again on US Microgravity Laboratory-2 (1995). Results from the experiment, which first appeared on the cover of *Science* magazine in 1986, provided many basic insights into the characteristics of gas flows in stars and gaseous planets. Hart and his colleagues were able to reproduce many of the flow patterns observed in gaseous planets under controlled and quantified conditions inside the Geophysical Fluid Flow Cell, thus providing a basis for analysis and physical interpretation of some of the distinctive dynamic features stars and gaseous planets.

## Combustion in Microgravity

### *What Is Fire Like in Microgravity?*

The crew of a spacecraft has few options in the event of a major fire. Fortunately, fires in spacecraft are rare; however, because both rescue and escape are uncertain possibilities at best, fire prevention, detection, and suppression continue to be an ongoing focus of NASA research even after more than 30 years of study.

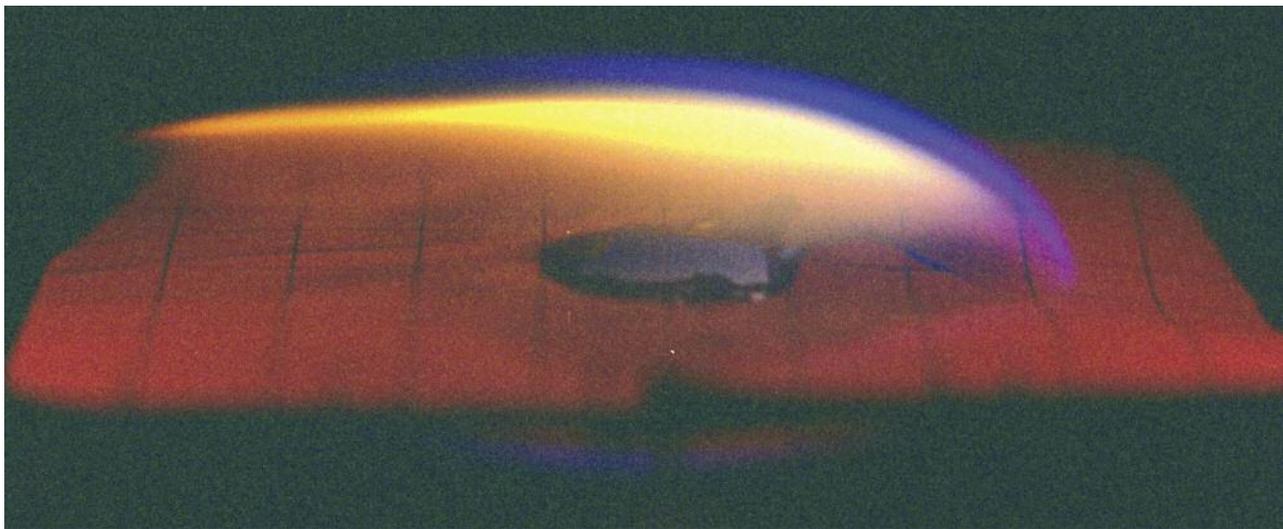


*This demonstrates the difference between flames on Earth (left) and in microgravity (right). The flame in microgravity is different because there is no upward buoyant force causing air to rise, so flames in space produce no buoyant convective flow that carry them upward.*

In the near-absence of gravity, fires ignite and spread differently than they do on Earth. Fires produce different combustion products, so experiments in space are essential to creating a science-based fire safety program. Research aboard the shuttle gave scientists an understanding of ignition, propagation, and suppression of fires in space. NASA is using the pioneering results of shuttle-era research to design a new generation of experiments for the ISS to help engineers design safer vehicles and better fire-suppression systems in the future.

The biggest difference between space- and Earth-based fires is that on Earth, the heat released by combustion

will cause a vigorous motion of the neighboring atmosphere as warm gas, less dense than the gas around it, rises due to its buoyancy under gravity. The upward buoyant flow draws surrounding air into the fire, increasing reaction rates and usually increasing the intensity of the fire. In space, buoyancy is negligible. Fire safety specialists must take into account the effects of cooling and ventilating airflows, which can significantly accelerate fires. Under “typical” conditions, however, combustion in space is slower than on Earth and is less complete. Soot particles are larger in space because particles spend more time growing in the fuel-rich reaction zone. As a result,



*NASA fire safety experiments examined the effects of weak cabin airflows on fires. Here, a piece of paper burns in a flow like those used to cool avionics systems in space. NASA research showed that weak flows can have a strong influence on material flammability.*

fire detectors in space need to be more sensitive to larger smoke particles than do fire detectors on Earth.

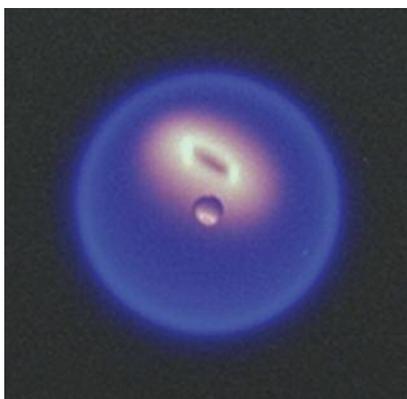
The experiments of David Urban of the NASA Glenn Research Center and his colleagues, included on the US Microgravity Payload-3 mission (1996), examined particulate-forming combustion in microgravity and observed that the larger particulates

produced in microgravity were often not detected by the sensor technology employed in detectors deployed on the shuttle, even though the detectors worked reliably on Earth. An alternate technology more sensitive to large particulates provided superior detection. This technology, which uses scattering of a laser beam by particles in the airstream, is now deployed aboard the ISS.

### ***Combustion of Fuels for Power***

Beyond its initial motivation, combustion research on the shuttle also helped scientists better understand the basic processes of burning hydrocarbon fuels that according to the US Department of Energy provide the US economy with 85% of its energy. Research by Forman Williams of the University of California, San Diego, and Fred Dryer of Princeton University, New Jersey, and their students on the

burning of fuel drops has been used by both General Electric (Fairfield, Connecticut) and Pratt & Whitney (East Hartford, Connecticut) to improve the jet engines they manufacture. Droplet combustion experiments in space produced well-controlled data that allowed Williams and Dryer to validate a comprehensive model for liquid fuel combustion. This model was integrated into the simulations that engine manufacturers use to optimize designs. Another experiment, led by Paul Ronney of the University of Southern California, Los Angeles, used microgravity to study the weakest flames ever created—100 times weaker than a birthday candle. Data on how combustion reactions behave near the limits of flammability were used to help design efficient hydrogen-burning engines that may eventually meet the need for clean transportation technologies.



*In nearly perfect weightlessness, an ethanol droplet on the Microgravity Science Laboratory-1 mission in 1997 burns with a spherical flame.*



## Commercial Ventures Take Flight

### Industry Access to Space Shuttle-inspired Innovation

NASA's charter included "seek and encourage ... the fullest commercial use of space." Acting in that direction, NASA promoted the Space Shuttle during the 1970s as a platform for industry.

Private industry is in business to provide goods and services for a financial return. Innovation is important. Microgravity—a physical environment that was new to industry at the time—proved to be intriguing. High-efficiency processing and free-floating containerless manipulation and shaping of materials could become reality with an absence of convection, buoyancy, sedimentation, and density differentiation. Highly purified biological separations, new combinations and structures of materials with valuable properties, and contamination-free solidifications prepared in orbit and returned to Earth became industry objectives for prospective space processing research.

In 1985, NASA and the National Bureau of Standards were responsible for the first sale of a product created in space. Designated "Standard Research Material 1960," this product was highly uniform polystyrene latex microspheres (specifically, sizes of 10 and 30 micrometers mean diameter) used in the calibration of scientific and medical instruments. Dozens of companies purchased "space beads" for \$350 per batch. This milestone came from an in-space investigation that produced both immediate science and an application.

#### Charles Walker

*Payload specialist on STS-41D (1984), STS-51D (1985), and STS-61B (1985).*

*"As a corporate research engineer I had dreamed of building an industry in space. Business conducted in orbit for earthly benefit would be important. The Space Shuttle could begin that revolution.*

*"The first industry-government joint endeavor agreement, negotiated in 1979 between NASA and the McDonnell Douglas Astronautics*

*Company, my employer, would facilitate space-enabled product research and development among different industrial sectors. It also presented an opportunity for me to realize that personal dream.*

*"NASA's astronauts had already successfully conducted limited company proprietary and public NASA research protocols during four flights with McDonnell Douglas' electrophoresis bioseparation equipment. Then NASA allowed one of our researchers to continue the work in person—exceedingly rare among researchers, and the first for industry.*

*"As the company's noncareer, non-NASA astronaut candidate, I had to pass the same medical and psychological screening as NASA's own. Training mixed in with my continuing laboratory work meant a frenzied year. Preparations for flight were exhilarating but they weren't free. McDonnell Douglas paid NASA for my flights as a payload specialist astronaut.*

*"Working with NASA and its contractor personnel was extraordinarily rewarding. I conducted successively more advanced applied commercial research and development as a crew member on board three shuttle missions over a 16-month period. It seemed the revolution had begun.*

*"I'm sorry to see these first-hand opportunities for applied research recede into history. Spaceflight is a unique, almost magical, laboratory environment. Disciplined research in microgravity can change human science and industry as surely as humanity's ancient experiences in the control of heat, pressure, and material composition."*



Charles Walker, payload specialist, works at the commercial Continuous Flow Electrophoresis System on STS-61B.



For-profit businesses vary in their need for scientific research. Companies often prioritize the application (product) as more important than its scientific basis. For them, reliable, practical, and cost-effective process knowledge is sufficient to create marketable products. But, if convinced that research can add value, companies will seek it. Various industries looked at the shuttle as an applied science and technology laboratory and, perhaps, even a platform for space-based product production. Industry found that production was not especially feasible in small spacecraft such as the shuttle, but they were successful with scientific-technology advancements.

McDonnell Douglas' space-based research and development section was the first to fly on seven missions, and these missions took place from 1982 to 1985. The electrophoresis applications work was technically a success. It improved bio-separations over Earth gravitational force processing. For example, when a cell-cultured human hormone erythropoietin (an anemia therapy) was to be purified 100 times better than ground-based separations, a 223 times improvement was obtained. Protein product throughput per unit of time also improved 700 times. After the Challenger accident (Space Transportation System [STS]-51L) in 1986, access to space for commercial efforts was severely restricted, thus ending the business venture. The demonstration of possibilities, together with McDonnell Douglas' investments in ground-based cell culturing and assaying, made for the effort's enduring advances.

In 2009, Astrogenetix (Austin, Texas)—a subsidiary of Spacehab/Astrotech (Austin, Texas)—was organized to

commercialize biotechnology products processed in microgravity. The company developed a proprietary means of assaying disease-related biomarkers through microgravity processing. This research objective was aimed at shortening and guiding drug development on Earth. From five rapid, shuttle-based flight opportunities (over a 15-month period), the company discovered a candidate for a salmonella vaccine. Even as Astrogenetix prepared to file an investigational new drug application with the US Food and Drug Administration, it was researching candidates for a methicillin-resistant *Staphylococcus aureus* vaccine. The company conducted this later work in microgravity on board the shuttle's final flights. Looking to the future, Astrogenetix is among the first commercial firms with an agreement from NASA for use of the International Space Station (ISS) national laboratory.

In the materials area, Paragon Vision Sciences (Mesa, Arizona) developed new contact lens polymers. During three flight experiments, the company looked into the effects of gravity-driven convection on long molecular chain formation, resulting in an improved ground-based process and Paragon's proprietary HDS® Technology materials product line.

Shuttle-based investigations amount to fewer than 6 months of laboratory time. Yet there have been significant outcomes across multiple disciplines. The national laboratory capability at the ISS seemingly offers a tremendous future of returns.



# 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.*

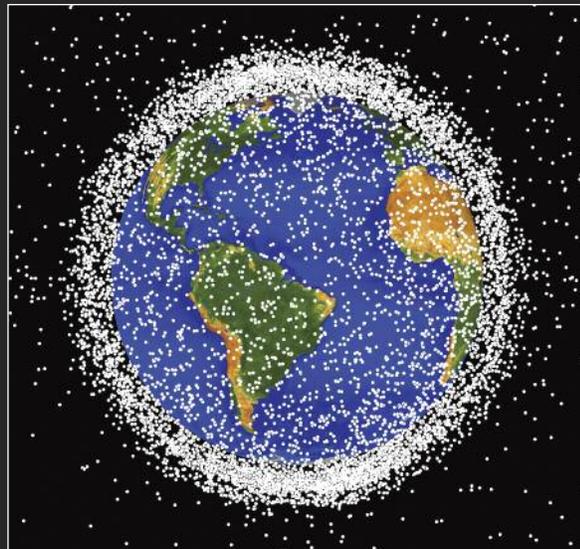
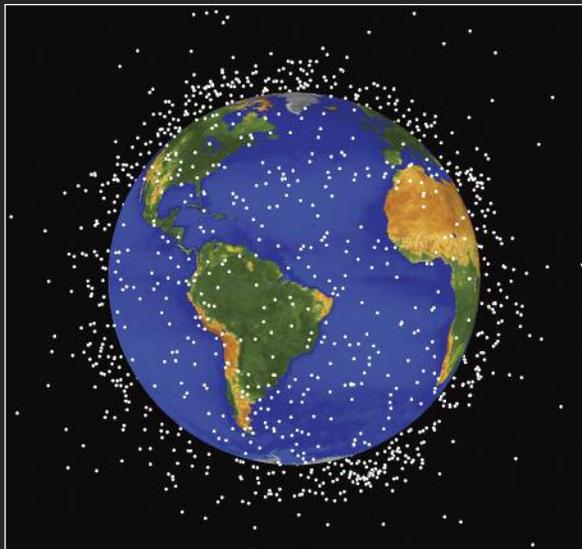
*What is environment like in space? Travel in space environment exposes vehicles and their occupants to: vacuum-like conditions, very low or zero gravity, high solar illumination levels, cosmic rays or radiation, natural micrometeoroid particles or fragments, and human-made debris—called “orbital debris”—from 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

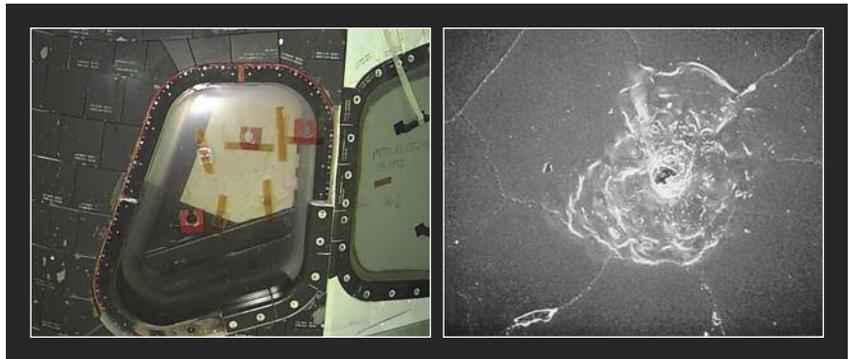
You have probably seen video clips of US Airways Flight 1549 glide into the Hudson River for landing in 2009 after a flock of geese disabled its engines. This incident highlighted the dangers of the local aviation environment on Earth. In space, while no geese posed a threat, fast-traveling debris consisting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

### 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,



*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).*

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 develops 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.

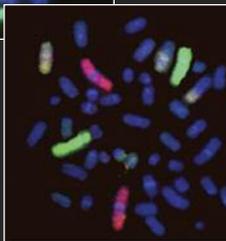
Radiation exposure in space is unavoidable and the potential for adverse health effects always remains. It is essential to understand the physics and biology of radiation interactions to measure and document astronaut exposures. It is equally important to conduct operations in such a way as to minimize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

### The Good, the Bad, and the Ugly

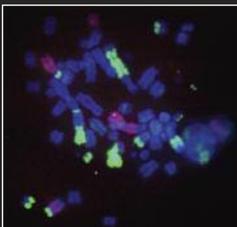
NASA is investigating a method of directly assessing the radiation risk by evaluating the amount of chromosome damage. Fluorescent chromosome painting techniques are used to paint Chromosome 1 (red), Chromosome 2 (green), and Chromosome 5 (yellow) in white blood cells to highlight rearrangement of DNA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

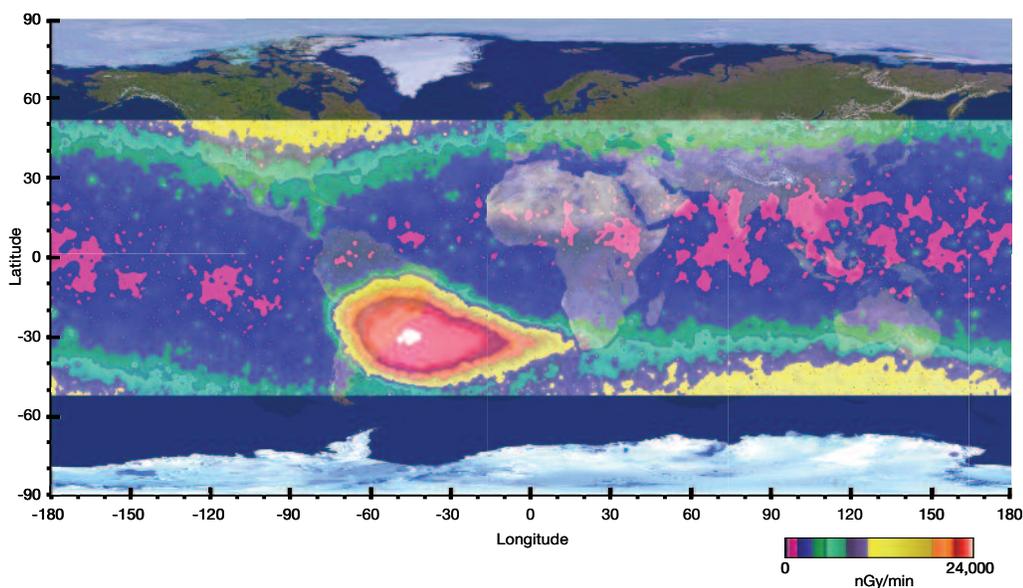
Researchers used a pool of approximately 300 astronauts and divided them by their total mission doses. The “low-dose” group had exposures less than 800 mrem (8 mSv), and the

“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

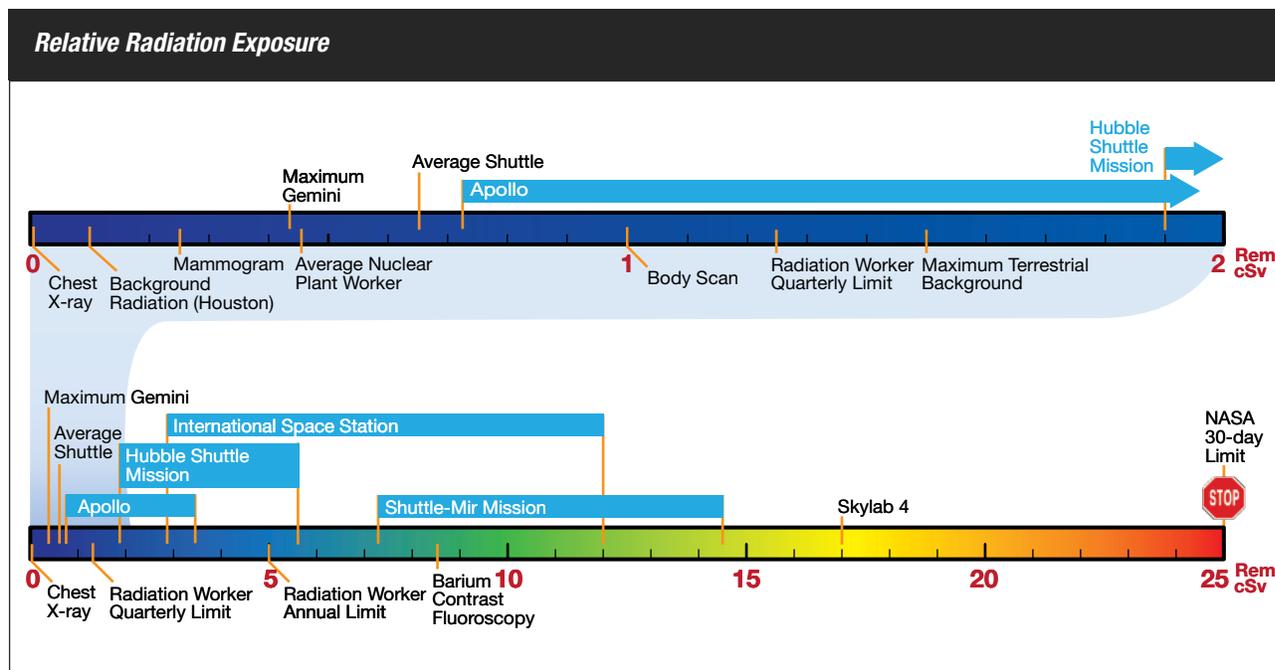
Scientists use two ways to measure radiation exposure to monitor astronaut health. The most frequent unit is the “dose” in units of rad or gray. Dose is solely a measure of the amount of energy deposited by the radiation. The second unit is “dose equivalent,” which represents a level of biological

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.





## **Space Shuttle Experiments Advance the Science of Radiation Shielding**

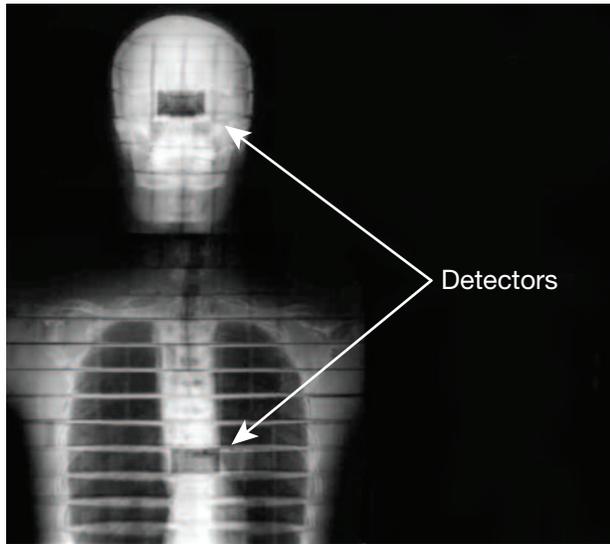
How do the characteristics of radiation change as it travels through shielding or the body? What is the relative exposure to the internal organs compared to external exposure measurements? Answers to these questions assist in evaluating astronaut exposure risks.

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



*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.*

“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.

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

## Anatomy of a Large Solar Energetic Particle Event

1. A collection of sunspots grows into an active region, intertwining magnetic fields.

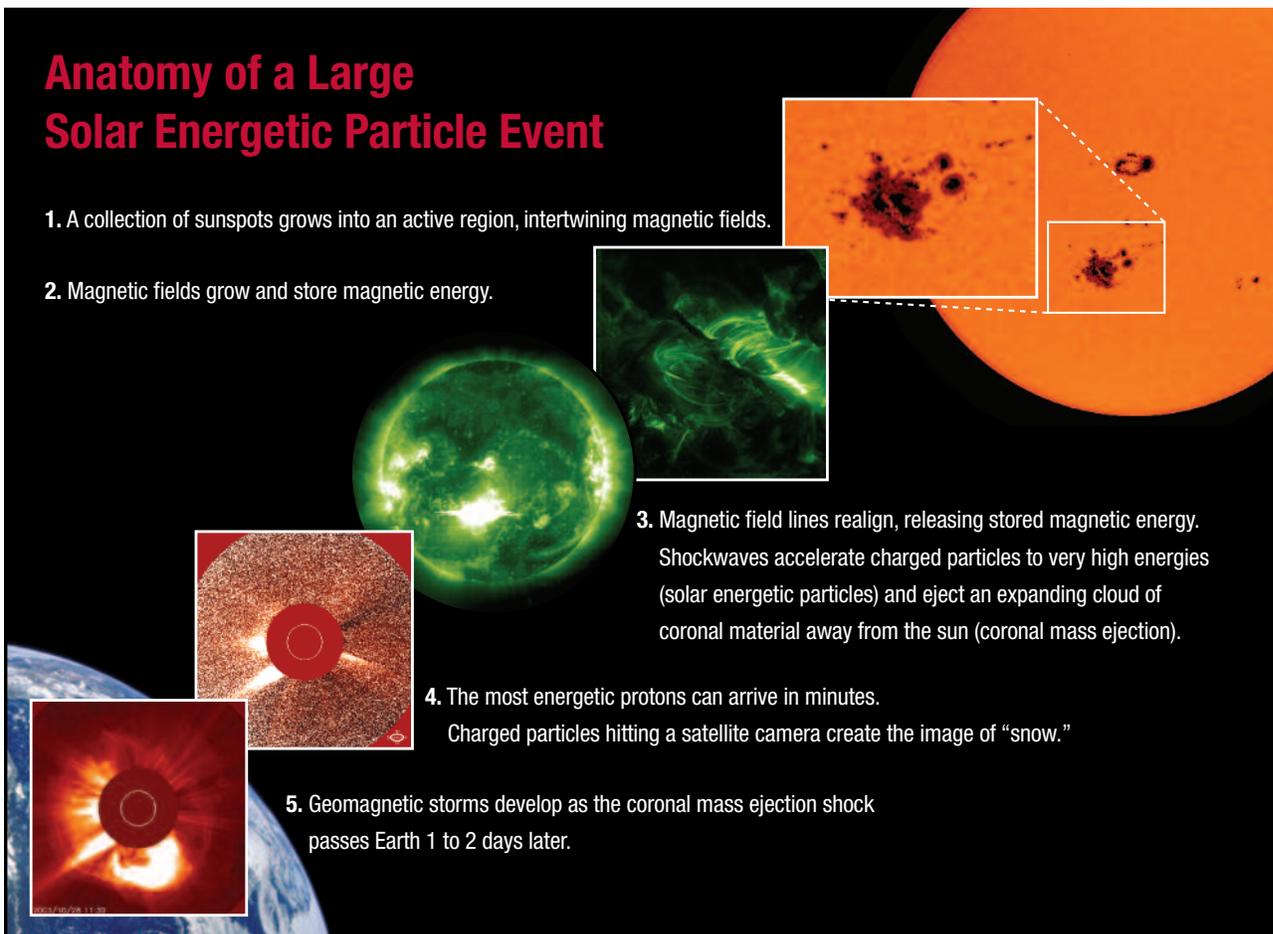
2. Magnetic fields grow and store magnetic energy.

3. Magnetic field lines realign, releasing stored magnetic energy. Shockwaves accelerate charged particles to very high energies (solar energetic particles) and eject an expanding cloud of coronal material away from the sun (coronal mass ejection).

4. The most energetic protons can arrive in minutes.

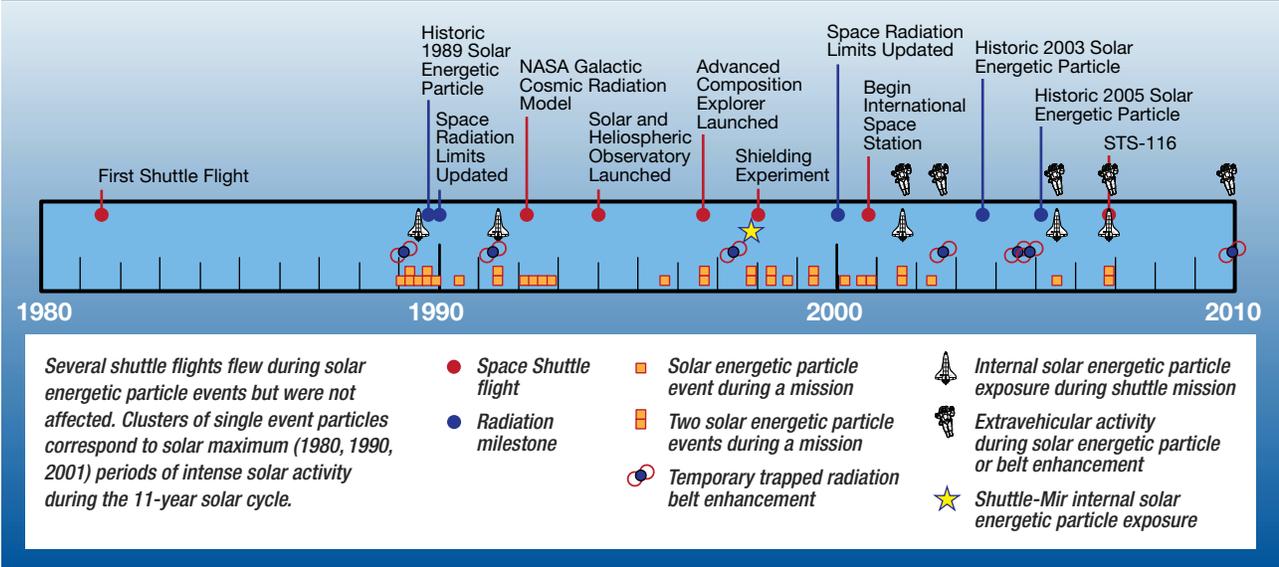
Charged particles hitting a satellite camera create the image of “snow.”

5. Geomagnetic storms develop as the coronal mass ejection shock passes Earth 1 to 2 days later.





## Space Radiation and the Shuttle Flying in Adverse Space Weather



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

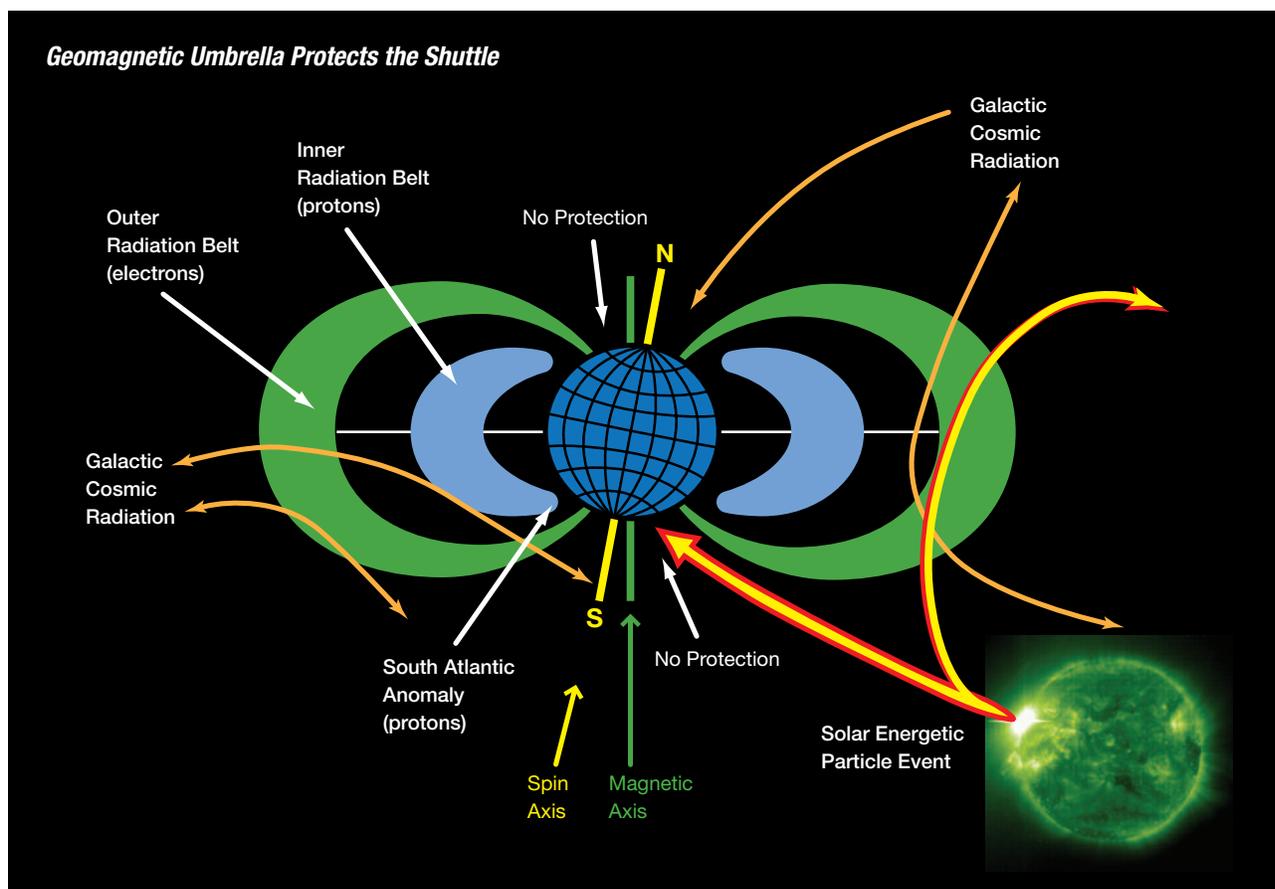
considerable protection to flight crews that flew low-inclination flights because the charged particles could not penetrate to the shuttle orbit. STS-34 flew in October 1989 during one of the historically largest solar energetic particle events but was unaffected by it because the geomagnetic field protected 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

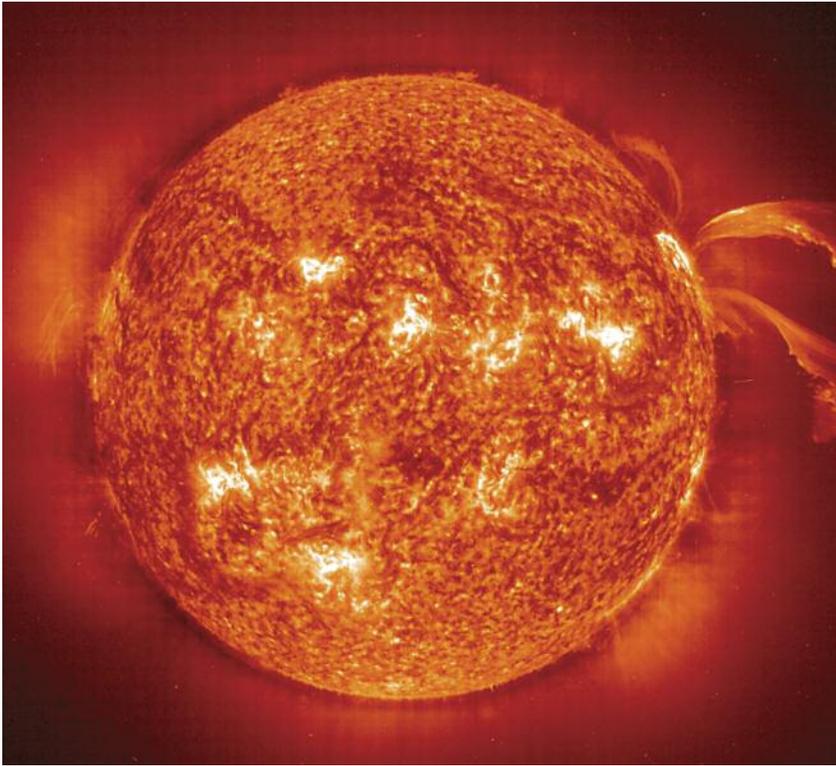
to solar energetic particle protons. During the remainder of the orbit, the crew was protected by the geomagnetic field and received no solar energetic particle dose.

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.*

## 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.

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.

