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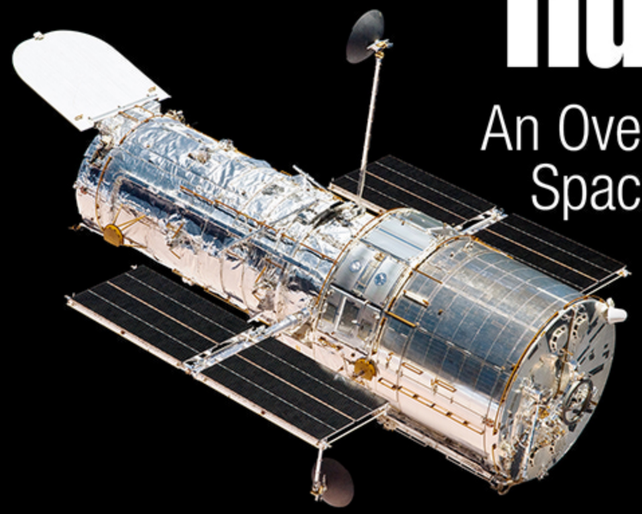

Hubble

An Overview of the Space Telescope

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Hubble

An Overview of the Space Telescope

This book is a joint project of NASA's Goddard Space Flight Center and the Space Telescope Science Institute under contract NAS5-26555.

The Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy, Inc., in cooperation with the European Space Agency and the National Aeronautics and Space Administration.

(Front cover) Launched in 1990, the Hubble Space Telescope *has revolutionized our understanding of the cosmos with its detailed images and spectra taken from high above the blurring and filtering effects of Earth's atmosphere. The mission operates as an ongoing partnership between NASA and the European Space Agency. Astronomers from around the world have used it to study everything from our celestial neighbors in the solar system to supermassive and immensely distant black holes.*

(Inside cover) This picture of Hubble *was taken from the Space Shuttle* Atlantis *at the conclusion of its final servicing by astronauts in May 2009. During five space walks, the astronauts installed two new instruments, repaired two older ones, replaced the telescope's batteries and gyros, and restored some damaged exterior insulation. The overhaul resulted in an observatory that was more powerful than at any time in its history.*

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Astronauts took this picture of Hubble *in May 2009 at the conclusion of Servicing Mission 4, documenting its final configuration.*

Hubble*'s observations have made new and significant scientific contributions to virtually every area of astronomy. Its detailed imagery of the Cat's Eye Nebula (NGC 6543), for example, revealed more intricate structures than ever imagined. This complex planetary nebula is suspected to surround a binary star that created its multiple gas shells, shockwaves, and stellar jets.*

Introduction

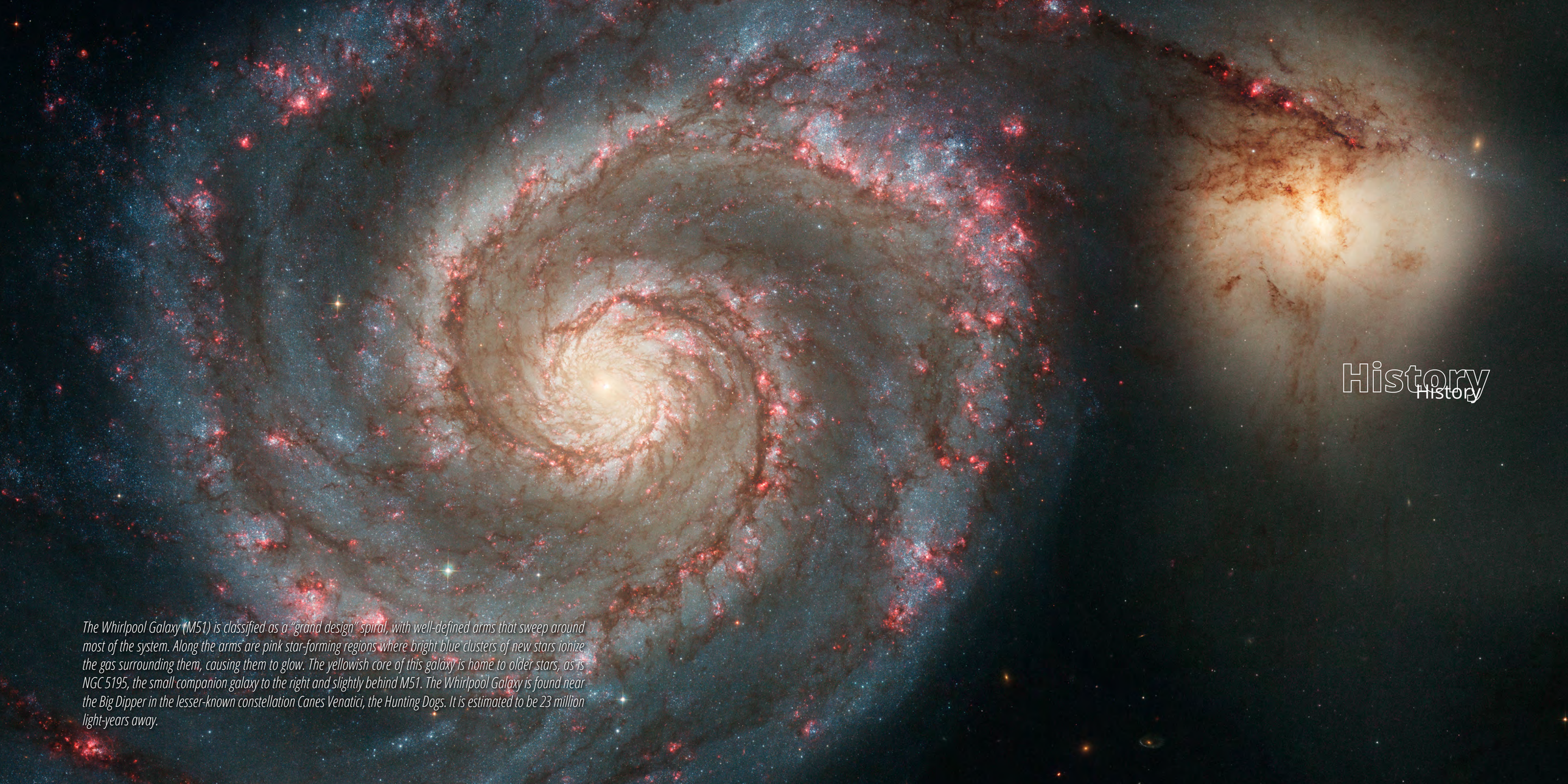
The history of science is marked by turning points associated with important discoveries made through revolutionary instruments. The field of microbiology, for example, was inaugurated by the discovery of cellular life through the invention of the microscope. The spectroscope revealed to us that light-emitting objects broadcast not just their colors, but information about the atomic processes which produced them. Through this, we learned the chemical makeup of stars. Likewise, particle accelerators exposed the astonishing complexity that exists on the quantum-physics scale.

The telescope holds an honorable position among these civilization-changing inventions. In 1609, the visionary scientist Galileo Galilei turned this newly invented device of his day to view the heavens. His observations showed conclusively that there were astronomical bodies that did not revolve around Earth, thus validating a radical, new model of the solar system and our place in it.

Four hundred years later, a telescope equipped with digital detectors and placed above the clouds continues to advance the legacy of Galileo's first influential spyglass. The *Hubble Space Telescope*, launched in 1990, orbits well above the optically degrading effects of Earth's atmosphere. Astronomers have used it to gain transformational, new views of many celestial objects—from tiny, nearby asteroids to immense and distant galaxies. In fact, *Hubble* observations played a leading role in discovering and characterizing the mysterious dark energy that now appears to pervade the cosmos.

The name *Hubble* has become synonymous with fruitful scientific exploration. The mission's success resonates strongly with the public as an archetype of human inquisitiveness and engineering ingenuity. It is a source of national pride and a model for international collaboration. The intellectual stimulus and sheer beauty of the telescope's findings have engaged the public and permeated its culture. *Hubble*'s scientific contributions are integrated yearly into the classroom curricula of millions of students and appear in textbooks, museums, and media sites worldwide. *Hubble* imagery has also demonstrably influenced art, dance, music, cinema, and fashion.

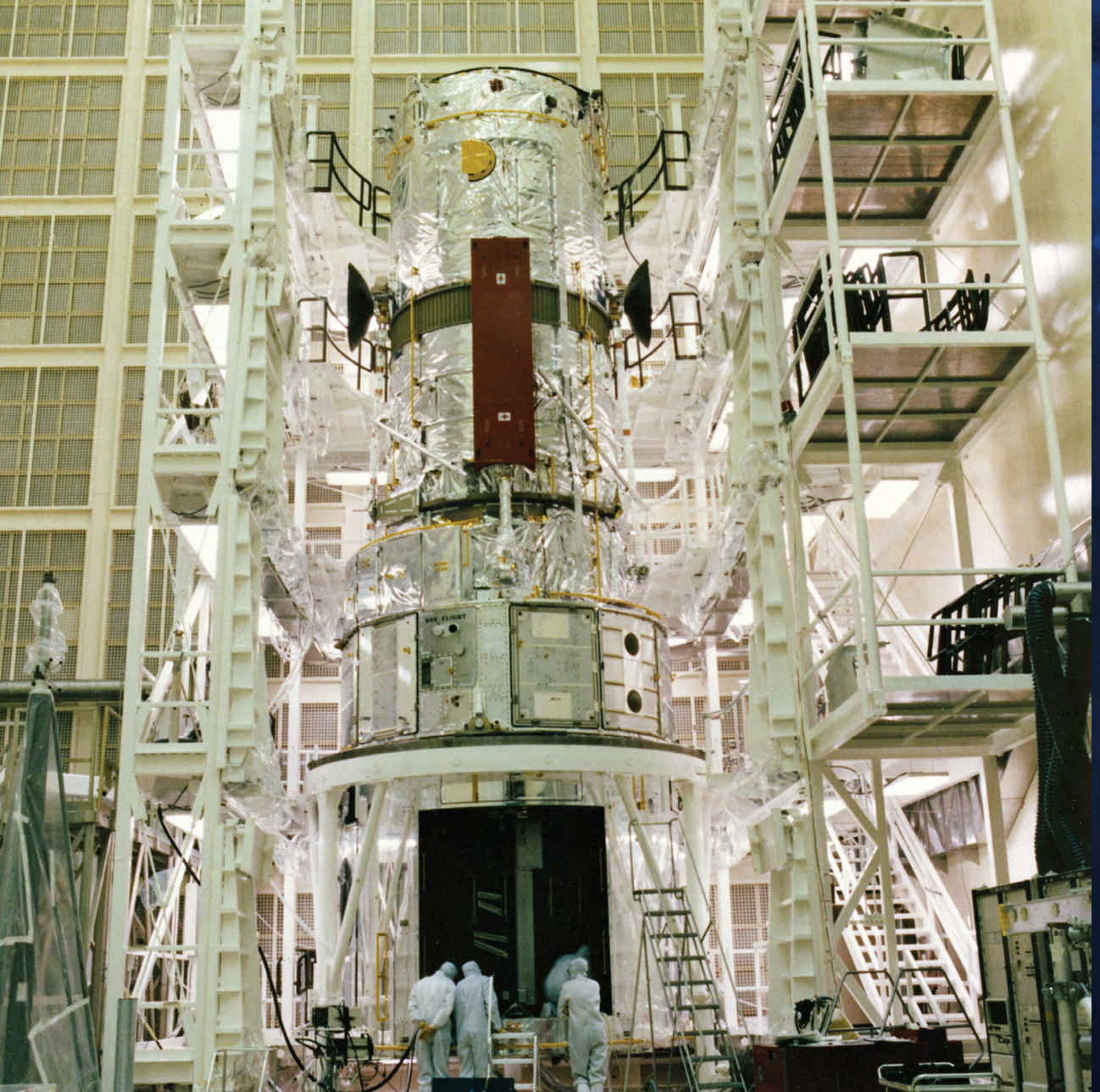
This book provides an overview of the historic space telescope with sections that briefly describe its history, design, operation and cultural impact.



History

History

The Whirlpool Galaxy (M51) is classified as a "grand design" spiral, with well-defined arms that sweep around most of the system. Along the arms are pink star-forming regions where bright blue clusters of new stars ionize the gas surrounding them, causing them to glow. The yellowish core of this galaxy is home to older stars, as is NGC 5195, the small companion galaxy to the right and slightly behind M51. The Whirlpool Galaxy is found near the Big Dipper in the lesser-known constellation Canes Venatici, the Hunting Dogs. It is estimated to be 23 million light-years away.



Hubble's History

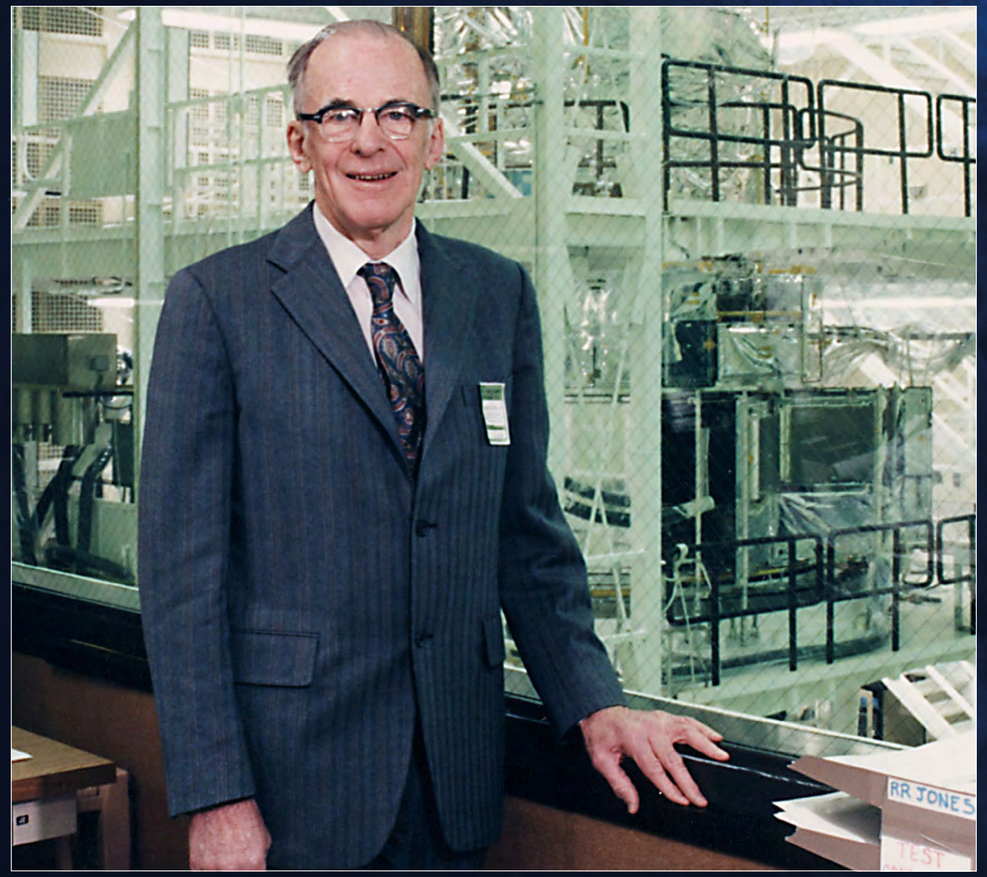
In April of 1990, *Hubble* first opened its eye on the universe and ushered in a new era of discovery. As successful and productive as it is now, the telescope produced some extremely daunting challenges for NASA and its international partners to make it so—from converting its exacting requirements into a workable and modular design to upgrading and repairing the observatory in orbit. Tackling these challenges has regularly punctuated the agency's storied history of human spaceflight with notable and memorable successes.

Hubble is the culmination of a dream as old as the space program itself. Theoretical physicist and astronomer Lyman Spitzer first proposed a large space telescope in 1946—more than a decade before the Soviet Union launched its first satellite and 12 years before the United States formed NASA. He knew that an observatory in space would be able to detect a wide range of wavelengths and would not suffer from the blurring effects of Earth's atmosphere. Spitzer proposed that such an observatory would reveal much clearer images than any ground-based telescope.

A tireless advocate of space astronomy, Spitzer was joined in the 1970s by colleagues John Bahcall, George Field, and others to champion the concept within the astronomical community, to the public, and to the Federal Government. In order to defray the cost, Congress required NASA to seek international collaboration on the mission. Thus, in 1976, the European Space Agency (ESA) was enlisted as a partner. ESA agreed to provide one of the science instruments, the telescope's solar panels, and 15 staff members to support science operations. Congress subsequently authorized the visionary mission in 1977.

Serious technological and managerial challenges—including funding and scheduling issues—arose during the turbulent years of *Hubble*'s design and manufacture. After extensive testing, *Hubble* was in the final stages of preparation for launch aboard the space shuttle when, in January of 1986, the nation suffered the loss of the Space Shuttle *Challenger* and its crew due to a flaw in the design of the shuttle's solid rocket boosters. Nearly three more years would pass before reengineered shuttle flights resumed and astronomers could realize the dream of

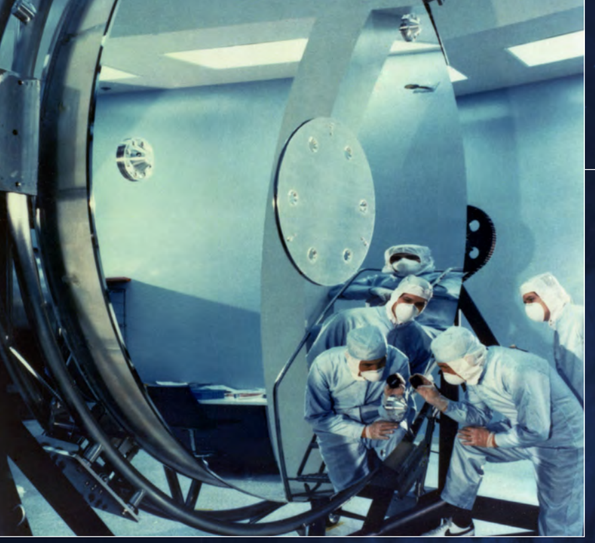
Hubble *went through the latter stages of its integration in a clean room at the Lockheed Missile and Space Company in California. Launched in 1990, the telescope is approximately 44 feet tall.*



Lyman Spitzer, an early proponent of space-based astronomy, helped usher the concept of a space telescope through Congress. The ultimate result of his efforts, the Hubble Space Telescope, *is visible in the cleanroom behind him.*

a working telescope in space. On April 25, 1990, astronauts on the STS-31 mission deployed *Hubble* into orbit from the Space Shuttle *Discovery* with every expectation that stunning new views would result.

After initial checkout of its critical systems in the Shuttle Discovery*'s cargo bay,* Hubble *was released into space on April 25, 1990 to begin its journey of discovery.*

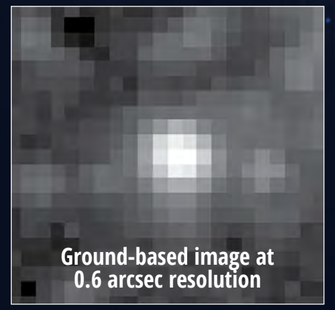


Workers inspect Hubble*'s primary mirror before installation.*

Hopes were quickly dashed when *Hubble* began returning data. Instead of crisp, point-like images of stars, astronomers saw stars surrounded by large, fuzzy halos of light. The problem was spherical aberration; the edges of *Hubble*'s large, primary mirror were ground too flat by just a fraction of the width of a human hair. Although perfectly smooth, the mirror could not focus light to a single point. It had been ground to the wrong shape because of a flaw introduced into the test equipment used to evaluate the mirror's curvature prior to launch.

Although engineers designed *Hubble* with many replaceable components, the primary mirror was not one of them. However, the ability for astronauts to upgrade the observatory in orbit ultimately led to a solution for this seemingly insurmountable problem. Even before NASA launched *Hubble*, engineers were hard at work building

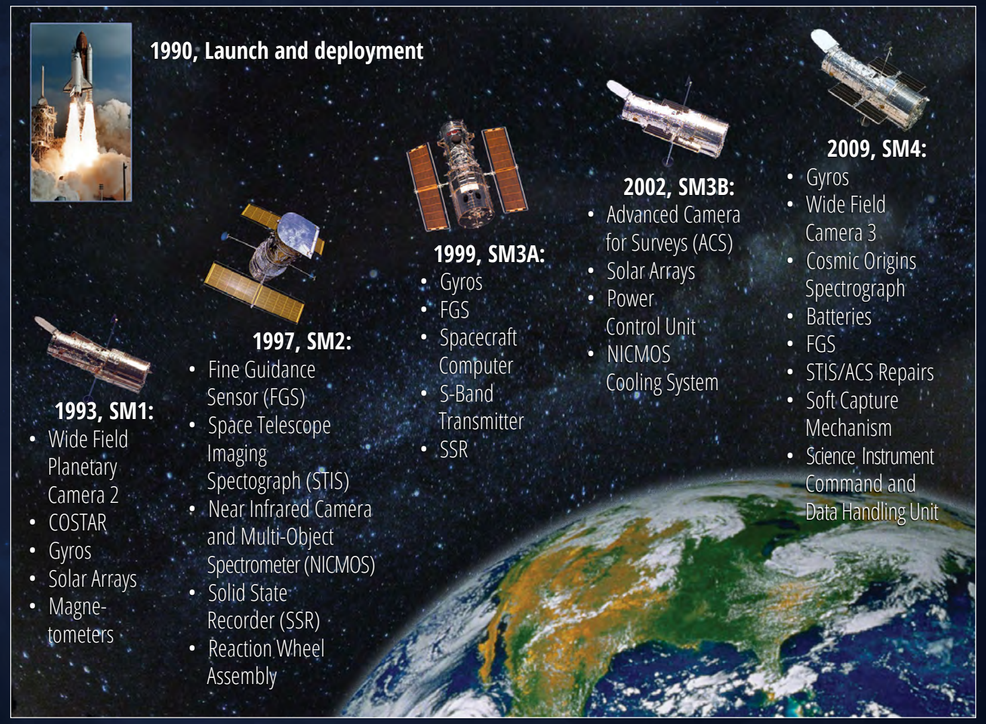
Despite the promise of remarkable pictures due to its position above Earth's atmosphere, Hubble*'s operation started dismally. The image at left shows a star field taken under ideal conditions from the ground. The center image shows the same view through* Hubble*'s initial camera, Wide Field and Planetary Camera 1 (WFPC1). While atmospheric blurring is gone and many more stars are visible, the effects of* Hubble*'s spherical aberration are also seen in the halo surrounding the bright central star. The sharply focused image at right was taken with the WFPC2, installed during the first servicing mission with integrated corrective optics.*



Ground-based image at 0.6 arcsec resolution

WFPC1 image (before servicing)

WFPC2 image (after servicing)



(Above) Following its launch, Hubble *was repaired, maintained, and upgraded by astronauts five times over a period of 19 years.* Hubble *is now more scientifically powerful than at any other point in its history. (Below) Pictured here are the mission patches for each of the five* Hubble *servicing missions.*

An error in the shape of Hubble*'s primary mirror prompted the development of a corrective device known as COSTAR. Installed in place of an existing instrument during the first servicing mission, COSTAR contained a mechanical arm of optics that was deployed into the telescope's light path, correcting its focus.*

an improved, second-generation camera. Called the Wide Field Planetary Camera 2 (WFPC2), this instrument was meant for installation by astronauts at a future date. Optics experts realized they could build corrective optics into this camera to counteract the flaw in the primary mirror. Meanwhile, *Hubble* scientists and engineers devised a set of nickel- and quarter-sized mirrors to remedy the effects of the primary mirror on *Hubble*'s other instruments. Labeled the Corrective Optics Space Telescope Axial Replacement (COSTAR), this device could be deployed into the light paths of the telescope's other instruments to focus their images properly.

In December 1993, astronauts installed COSTAR during a series of spacewalks. This ambitious endeavor successfully restored *Hubble*'s vision to the designers' original expectations. On subsequent days during the mission, astronauts also upgraded various components of the spacecraft including ESA-provided solar arrays and associated control electronics. During the many years following that historic first servicing mission, *Hubble* has amassed a spectacular data treasure trove for the world—thousands of clear, deep views of the universe. Astronomers from around the world have used the telescope to answer some of the most pressing astronomical questions of our time, and its discoveries have also spawned a host of follow-up investigations.

As new technology became available, *Hubble*'s innovative, modular design enabled astronauts to upgrade and enhance it through four additional servicing missions. In 1997, Servicing Mission 2 vastly improved *Hubble*'s spectroscopic capabilities with the insertion of the Space Telescope Imaging Spectrograph (STIS). Using it, astronomers confirmed the existence of supermassive black holes in the centers of galaxies and also showed that black-hole masses are tightly correlated with the masses of the surrounding ancient stellar population. During the 1997 service call, the addition of the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) opened *Hubble*'s view of the universe to a new spectral regime—those wavelengths slightly longer than visual light. This near-infrared sensitivity has helped astronomers untangle the complex processes in the early universe that led to the formation of galaxies, including our own Milky Way.

During Servicing Mission 3A in 1999, spacewalking astronauts enhanced many of *Hubble*'s subsystems—replacing its central computer; adding a new, solid-state data-recording system to replace its aging magnetic tape drives;

and swapping out the gyroscopes needed for pointing control. When a premature loss of solid-nitrogen coolant cut short NICMOS's operational life, engineers devised innovative mechanical refrigeration technology as an alternate way of cooling its detectors to their operating temperature of –320°F (–196°C). On Servicing Mission 3B in 2002, this cooling system was retrofitted to NICMOS, which brought the instrument back to life. During that mission, astronauts also replaced the productive, but aging, ESA-built Faint Object Camera with a new, more powerful camera—the Advanced Camera for Surveys (ACS)—providing a tenfold improvement over WFPC2.

Servicing Mission 4 (SM4), the final servicing mission to *Hubble* in 2009, brought the telescope to the apex of its scientific capabilities. Astronauts installed two new instruments: the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3 (WFC3). COS is the most sensitive ultraviolet spectrograph ever built for *Hubble*. It probes the cosmic web, the large-scale structure of the universe, whose form is determined by the gravity of dark matter and is traced by the spatial distribution of galaxies and intergalactic gas. WFC3 is sensitive across a wide range of wavelengths (colors) including infrared, visible, and ultraviolet light. It contains a variety of broad- and narrow-band filters, as well as grisms (spectroscopic elements), which enable wide-field, low-resolution,

Positioned on the remote manipulator system, Mike Good transports the assortment of tools required to repair the Space Telescope Imaging Spectrograph during Servicing Mission 4. Included among them is the ingenious fastener capture plate (blue rectangular device floating above him) that will trap more than 100 non-captive screws during removal of the instrument's electronics cover.

Space Shuttle Atlantis *and its seven-member STS-125 crew launched on time at 2:01 p.m. (EDT) on May 11, 2009 from pad 39A at NASA's Kennedy Space Center. The STS-125 mission was the final servicing mission to* Hubble. *(Photo credit: NASA/M. Soluri)*

slitless spectroscopy with unparalleled sensitivity. Scientists use WFC3 to study planets in our solar system, the formation histories of nearby galaxies, and early and distant galaxies. Astronauts also made in-orbit repairs to two instruments already on *Hubble* : STIS and ACS. Neither was designed to be serviced in space, so both repairs required new tools and procedures. STIS had stopped working in 2004; to recover it, astronauts replaced a low-voltage power-supply board. ACS had suffered a partial failure in early 2007 after operating exquisitely for nearly five years. To fix it, astronauts replaced failed circuit boards and added a new power supply. These steps effectively restored its high-efficiency imaging in both the visible and ultraviolet portions of the spectrum. Rounding out the mission, various aging components of the spacecraft were upgraded, including the gyroscopes, batteries, and the science instrument command and data handling unit.

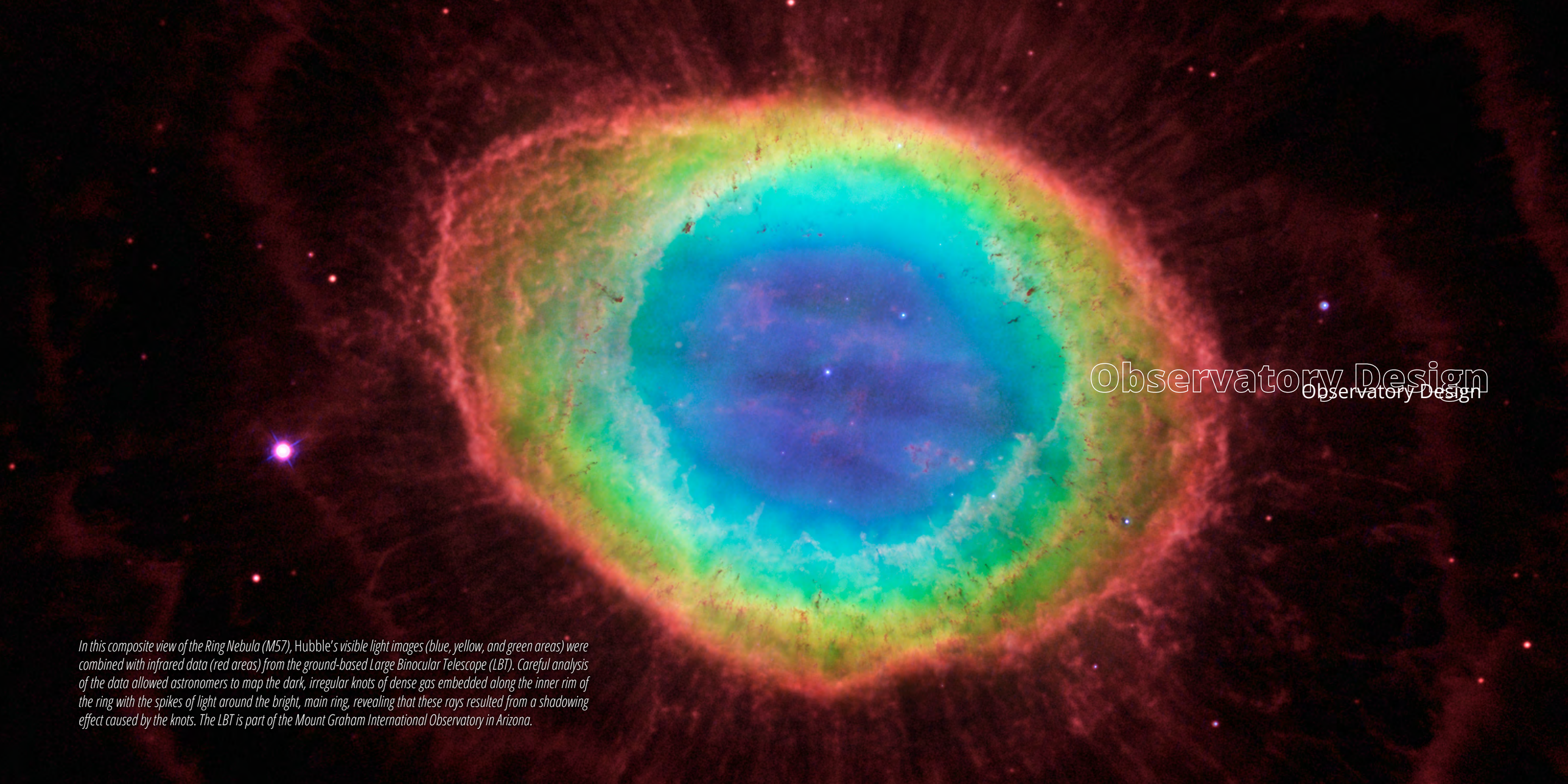
Hubble is now functioning at its peak scientific performance. Its pictures and spectra fill modern astronomy textbooks. More peer-reviewed scientific papers have been published using *Hubble* data than for any other spacecraft. Millions of visits occur monthly to the mission's public outreach websites, and *Hubble* images appear regularly in news media.

Through its long history of travail and triumph, the *Hubble Space Telescope* mission has combined the best of NASA's robotic and human space flight programs with an exemplary partnership with ESA. One of the most powerful and productive scientific tools ever developed, *Hubble* continues to capture scenes of profound beauty and intellectual challenge. Thousands of astronomers from around the world have used *Hubble* for boundary-breaking research in virtually all areas, including the physics of dark matter and dark energy. Not since the days of Galileo has a telescope provided such insight and so broadly piqued the curiosity of the human race.

The latest on Hubble *and its discoveries can be found at http://hubblesite.org.*

The story of Servicing Mission 4 was captured in the IMAX movie Hubble 3D. (Above) Three-time Academy-Award nominee Leonardo DiCaprio records narration for Hubble 3D. (Photo credit: © 2010 Warner Bros.) (Right) The promotional movie poster for Hubble 3D. (Photo credit: © 2010 Warner Bros.)

(Above) Attendees enjoying the movie. (Photo credit: NASA/P. Alers) (Right) Five of the seven crewmembers of STS-125 enjoy the premiere of Hubble 3D at a special event at the Smithsonian National Air and Space Museum (Photo credit: Smithsonian National Air and Space Museum)



Observatory Design

Observatory Design

In this composite view of the Ring Nebula (M57), Hubble*'s visible light images (blue, yellow, and green areas) were combined with infrared data (red areas) from the ground-based Large Binocular Telescope (LBT). Careful analysis of the data allowed astronomers to map the dark, irregular knots of dense gas embedded along the inner rim of the ring with the spikes of light around the bright, main ring, revealing that these rays resulted from a shadowing effect caused by the knots. The LBT is part of the Mount Graham International Observatory in Arizona.*

Observatory Design

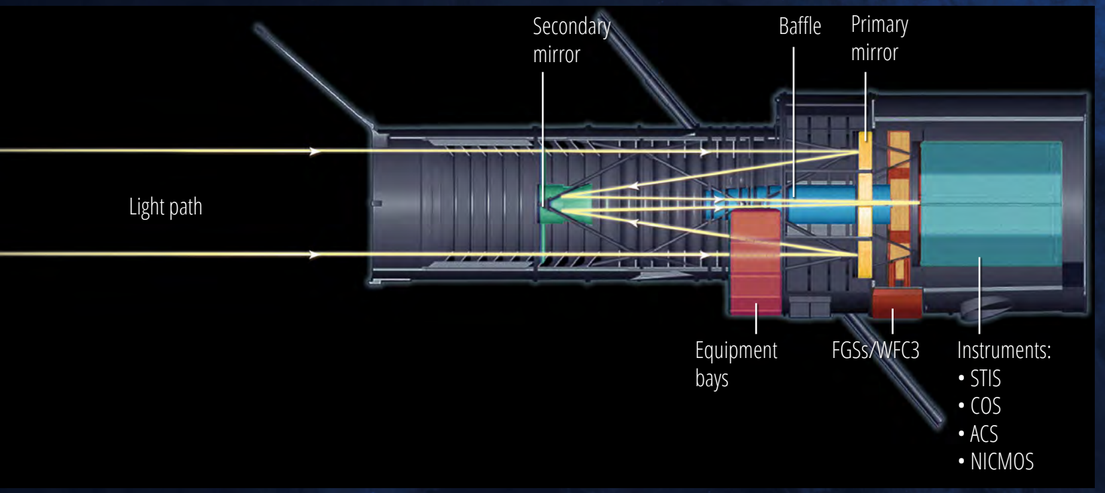
Orbiting 360 miles above Earth, the *Hubble Space Telescope* is positioned high above the blurring effects of the atmosphere. From this vantage point, it captures images with 10 times the typical clarity of any ground-based telescope and views not only visible light, but also wavelengths of near-infrared and ultraviolet light that cannot reach Earth's surface. To operate from orbit, the observatory works like any other scientific or imaging spacecraft; it converts the optical data it collects into electrical signals that are transmitted back to Earth. It must also withstand the airless, high-radiation, and harsh thermal environment of space.

Unlike most other spacecraft, however, *Hubble* was designed to be serviced periodically by astronauts and so was built with modular components that are astronaut-friendly to handle and replace. This design strategy has enabled it to operate longer than ordinary spacecraft and to benefit from the technological advancements of the last two decades. Astronauts have visited the telescope five times to upgrade its computers, mechanisms, and instruments. These servicing missions have kept the observatory at the forefront of discovery by providing it with increasingly sensitive and accurate components. The last of these servicing calls was in May 2009.

Hubble is big. Excluding its aperture door and solar arrays, the spacecraft is 43.5 feet (13.3 meters) long—about as high as a four-story building—and 14 feet (4.3 meters) in diameter at its widest point. Altogether, it would weigh about 25,000 pounds (11,340 kilograms) on the ground, although it is weightless in orbit. About the size of a large school bus, it filled the payload bay of the Space Shuttle *Discovery* when carried aloft in April 1990.

The heart of *Hubble* is its 7.8-foot (2.4-meter) primary mirror, which collects approximately 40,000 times as much light as the human eye. The telescope's optical layout is known as a Ritchie-Chrétien Cassegrain design. Incoming light bounces off the primary mirror, up to a secondary mirror, and back through a hole in the primary mirror, where it comes to a focal plane that is shared among the suite of scientific instruments. A series of baffles painted flat black and mounted within the telescope suppress stray or scattered light from the Sun, Moon, or Earth.

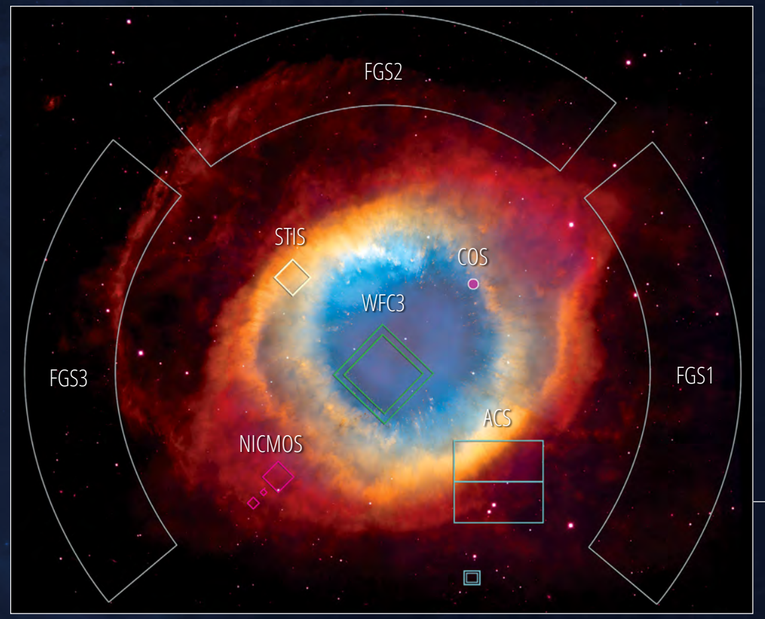
Astronauts Steven Smith and John Grunsfeld work to replace Hubble*'s gyroscopes during Servicing Mission 3A in December 1999. Over 20 years and five servicing missions, astronauts upgraded the telescope with new components ranging from improved instruments to more modern computers, a feat made possible by the spacecraft's original modular design.*



Hubble*'s 1,825-pound, 7.8-foot (2.4-meter) diameter primary mirror collects light from its astronomical target and reflects it to a 12-inch (0.3-meter) diameter secondary mirror located in the optical tube. This secondary mirror then reflects the light through a hole in the primary mirror to form an image at the telescope's focal plane. There it is intercepted by pick-off mirrors that pass it into the scientific instruments.* Hubble*'s mirrors are made of ultra-low expansion glass kept at a "room temperature" of about 70°F (21°C) to avoid warping. The reflecting surfaces are coated with a 3/1,000,000-inch layer of pure aluminum and protected by a 1/1,000,000-inch layer of magnesium fluoride that also makes the mirrors more reflective to ultraviolet light.*

Hubble's optical system is held together by a supporting skeleton, a truss measuring 17.5 feet (5.3 meters) in length and 9.6 feet (2.9 meters) in diameter. The 252-pound (114.3-kilogram) truss is a stiff, strong, lightweight graphite-epoxy material that resists expansion and contraction in the extreme temperatures of space. A similar material is used in the production of golf clubs, tennis racquets, and bicycles.

The narrow top section of the *Hubble*'s tube-shaped body, known as the forward shell, houses the telescope's optical assembly. Most of the control electronics for the observatory sit in bays placed around the middle of the telescope, known as the Support Systems Module (SSM), where the spacecraft body widens. This middle section is near the telescope's center of gravity and hence home to the telescope's four 100-pound reaction wheels—the spinning flywheels *Hubble* uses to reorient itself. Astronauts can easily access the devices within the SSM, and a number of these have been replaced or upgraded during servicing missions.



The primary and secondary mirrors of Hubble *form an image in the focal plane of the telescope whose light is shared by the instruments and Fine Guidance Sensors (FGSs). Seen here are the locations of the instrument fields of view within the focal plane. In the background is a scale image of the Helix Nebula. Two stars found among the three FGS fields of view are selected as guide stars for the observation.*

At the back end of the spacecraft, the "aft shroud" houses the scientific instruments, gyroscopes, star trackers, and other components. The aft shroud has room for five scientific instruments. Over the years, NASA and ESA have manufactured 15 scientific instruments for *Hubble*. Through advances in technology, each new generation of instruments has brought enormous improvements to the scientific capabilities of the observatory. The current complement consists of the Wide Field Camera 3 (WFC3), the Cosmic Origins Spectrograph (COS), the Advanced Camera for Surveys (ACS), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), and the Space Telescope Imaging Spectrograph (STIS).

All of the spacecraft's interlocking sections—the forward shell, SSM, and aft shroud—were designed to provide a benign thermal and physical environment in which sensitive telescope optics and scientific instruments can operate. They are encased in a thin aluminum shell and blanketed by many thin layers of insulation. In a single orbit around Earth, the exterior surface of *Hubble* varies in temperature from –150°F to +200°F (–101°C to +93°C).

Hubble Space Telescope

Primary mirror
Hubble's primary mirror is 7.8-feet (2.4-meters) in diameter. It is made of a special glass coated with aluminum and a compound that reflects ultraviolet light. It collects light from the telescope's targets and reflects it to the secondary mirror.

Secondary mirror
Like the primary mirror, Hubble's secondary mirror is made of special glass coated with aluminum and a compound to reflect ultraviolet light. It is 12 inches (30.5 centimeters) in diameter and reflects the light back through a hole in the primary mirror and into the instruments.

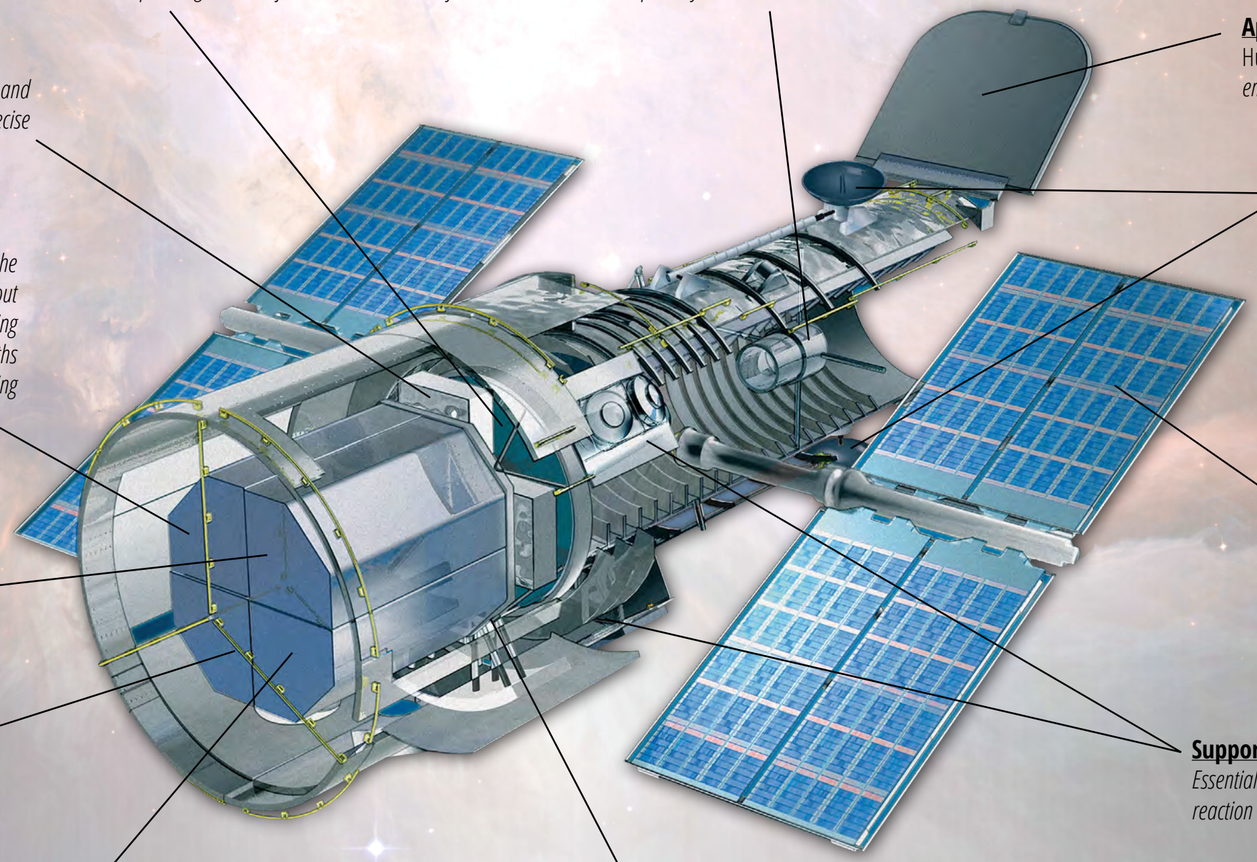
Fine Guidance Sensors
Hubble has three Fine Guidance Sensors (FGSs). Two are needed to point and lock the telescope on target, while the third can be used for astrometry, the precise measurement of stellar positions.

Space Telescope Imaging Spectrograph
The Space Telescope Imaging Spectrograph (STIS) principally performs spectroscopy—the separation of light into its component colors (or wavelengths) to reveal information about an object's chemical content, temperature, density, and motion. STIS also performs imaging in most of the ultraviolet bands, the entire optical wavelength band, and some wavelengths extending into the near-infrared. STIS was repaired on orbit in 2009 by astronauts during Servicing Mission 4.

Cosmic Origins Spectrograph
The most sensitive ultraviolet spectrograph ever flown, the Cosmic Origins Spectrograph (COS) measures the structure and composition of matter concentrated in the "cosmic web." It also studies how galaxies, stars, and planets formed and evolved, and is helping determine how the elements needed for life first formed.

Near Infrared Camera and Multi-Object Spectrometer
The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) is an instrument for near-infrared imaging and spectroscopic observations of many types of astronomical targets.

Advanced Camera for Surveys
The Advanced Camera for Surveys (ACS) was designed primarily for wide-field imagery in visible wavelengths, although it can also detect ultraviolet and near-infrared light. Its wide-field and high-resolution channels failed in 2007, leaving only a "solar-blind" (ultraviolet) channel operational. During Servicing Mission 4, astronauts were able to repair the wide-field channel, restoring the telescope's capability to capture high-resolution, wide-field views.



Aperture door
Hubble's aperture door can close, if necessary, to prevent light from the Sun from entering and potentially damaging the telescope or its instruments.

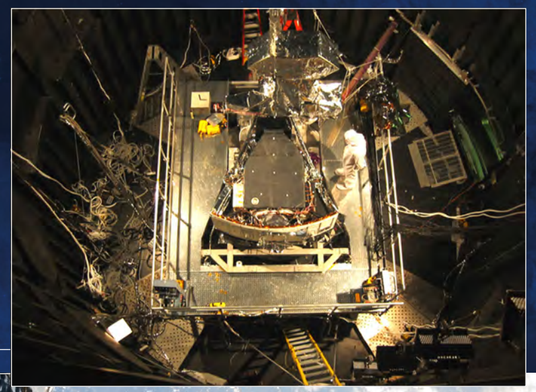
Communication antennas
Digital images and spectra stored in Hubble's solid-state recorders are converted to radio waves and then beamed through one of the spacecraft's high-gain antennas (HGAs) to a NASA communications satellite, which relays them to the ground. Because the HGAs would extend off the page above and below the spacecraft image, they are shown here pressed against the side of the telescope in their "berthed positions." This is how they were configured at launch.

Solar panels
Hubble's current set of rigid solar panels use gallium-arsenide photovoltaic cells that produce enough power for all the science instruments to operate simultaneously. The first and second sets were larger, flexible panels, but produced less power.

Support systems
Essential support systems such as computers, batteries, gyroscopes, reaction wheels, and electronics are contained in these areas.

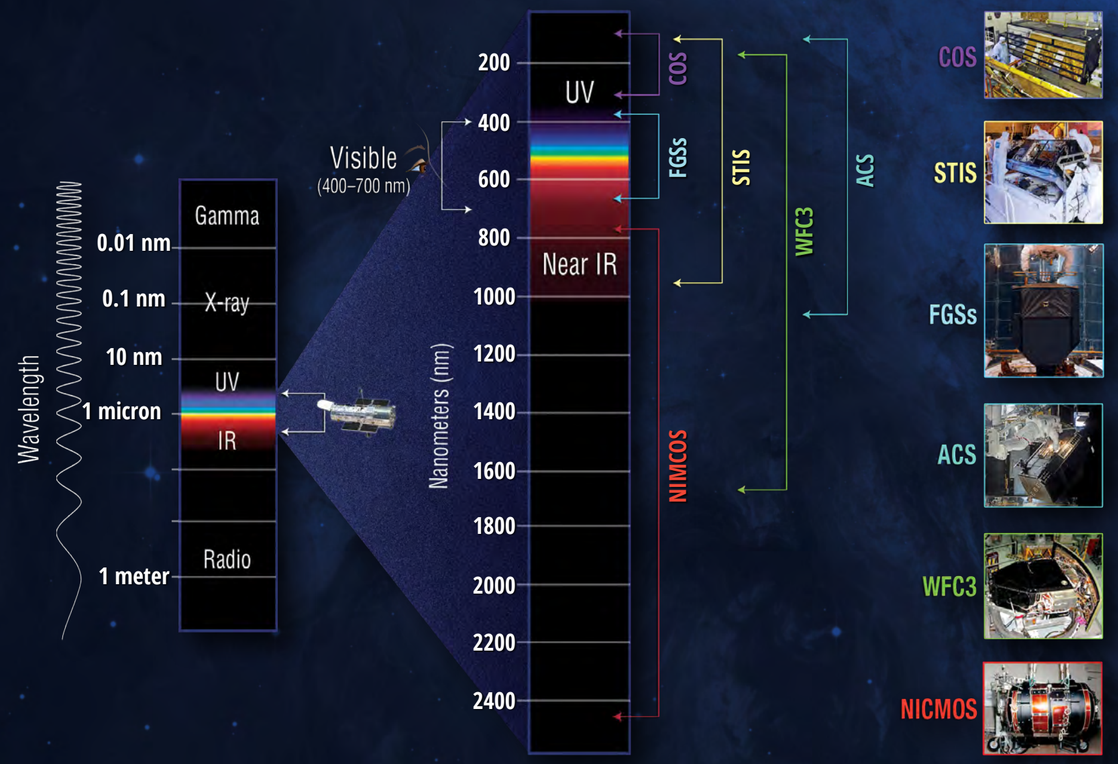
Wide Field Camera 3
With panchromatic vision extending from the ultraviolet through the visible and into the infrared, the Wide Field Camera 3 (WFC3) enhances Hubble's capability not only by seeing deeper into the universe, but also by providing wide-field imagery in these three regions of the electromagnetic spectrum. WFC3 is used to study galactic evolution, stellar populations in nearby galaxies, dark energy, and dark matter.

(Right) The Wide Field Camera 3 instrument sits at the bottom of the large Space Environment Simulator at NASA's Goddard Space Flight Center as technicians prepare it for an extended thermal-vacuum test.



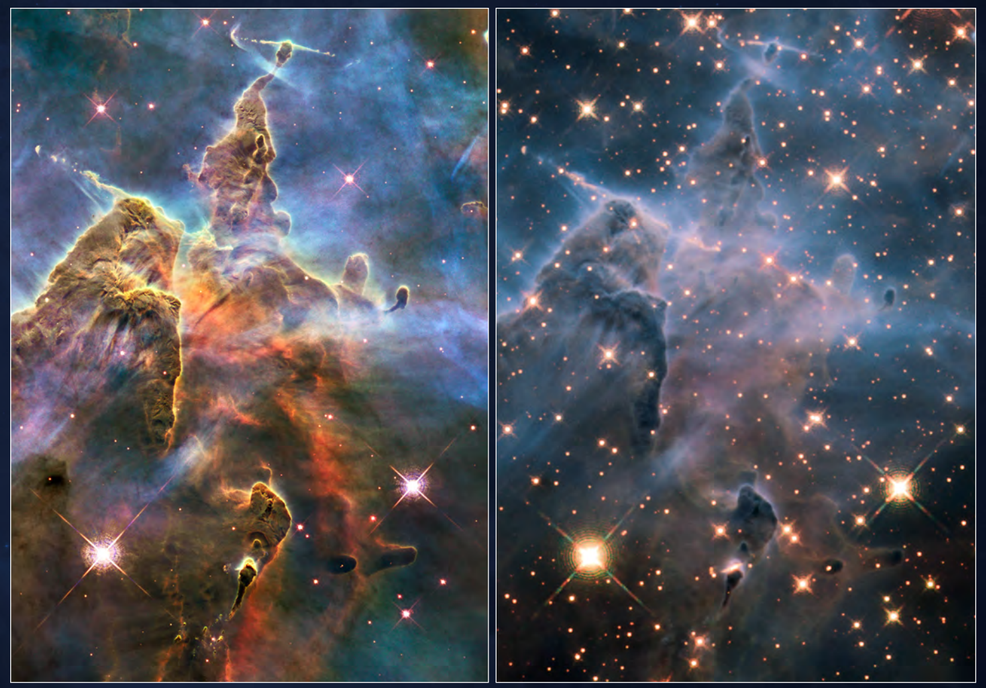
(Below) With the installation of the Wide Field Camera 3, Hubble *gained a sensitive new tool to study the cosmos. Here, astronaut Andrew Feustel is seen maneuvering the camera toward the telescope during the first of five successful spacewalks during Servicing Mission 4 in May 2009.*

(Opposite page) The Ball Aerospace company designed and built Hubble*'s Space Telescope Imaging Spectrograph (STIS). Installed by astronauts in 1997, STIS is used to study such objects as black holes, new stars, and massive extrasolar planets. A low-voltage power supply failure in 2004 rendered STIS inoperable. During the final servicing mission to the telescope in 2009, astronauts successfully replaced the failed unit, bringing STIS back into service. STIS is one of the many complex scientific instruments that have flown on* Hubble.



Hubble's instruments collectively observe wavelengths (measured in nanometers) from ultraviolet through infrared. Each instrument was designed to operate in a particular wavelength range and function as an imaging camera or a spectrometer, though some instruments do both. The Fine Guidance Sensors (FGSs) not only help the telescope stay locked on target, but can be used as science instruments to accurately determine the relative position of stars.

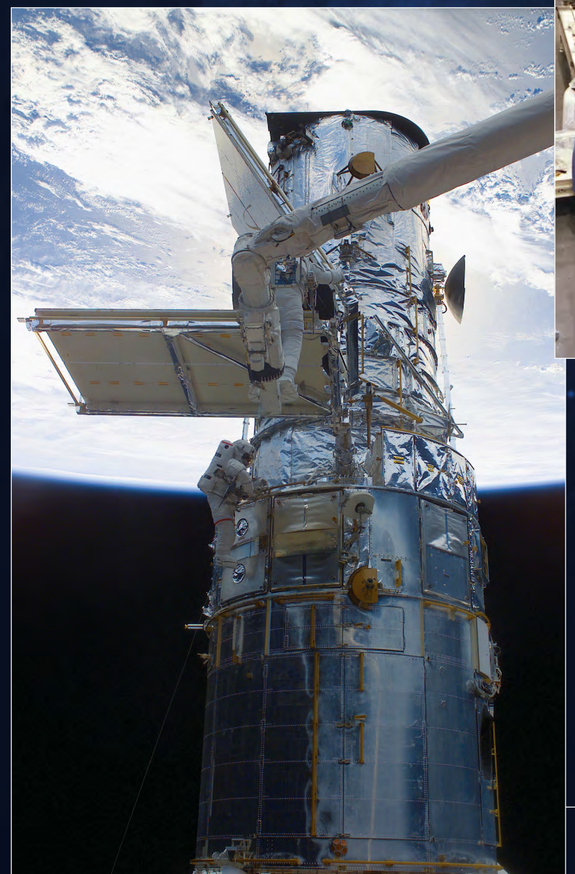
Despite these wide thermal swings, the interior of the telescope is maintained by the thermal control system to a narrow temperature range—in many areas to a comfortable "room temperature." Heat sensors, radiators, electric heaters, insulation, and special paints all work in concert to minimize the expansion and contraction that could alter the telescope's focus. They also keep the electronic devices inside the spacecraft at their proper



These two images of a three-light-year-high pillar within the Carina Nebula demonstrate how observations taken in visible and near-infrared light by Hubble *can reveal dramatically different and complementary views of an object. In the visible-light view on the left, strong radiation and energetic streams of charged particles from hot young stars in the nebula are seen shaping and compressing the pillar, causing additional new stars to form within it. Two of these infant stars are releasing bidirectional jets of gas seen to protrude from the tops of their respective clouds. In the near-infrared-light view on the right, the presence of hundreds of additional stars is revealed as these longer wavelengths penetrate through much of the gas and dust in the nebula.*

operating temperatures. During the last three servicing missions, astronauts replaced sections of *Hubble*'s external insulation that had deteriorated from exposure to the harsh conditions of space, adding panels called New Outer Blanket Layers over portions of the spacecraft.

Hubble nominally operates via stored commands, computer-based instructions that have associated execution times. The Flight Operations Team (FOT) at NASA's Goddard Space Flight Center in Greenbelt, Maryland, typically sends a day's worth of commands at once, although they can also command the spacecraft in real time during emergencies, engineering tests, or other such scenarios. These commands are uplinked to the spacecraft—and its scientific and engineering data returned to the ground—via a system of NASA geosynchronous communications satellites called the Tracking and Data Relay Satellite System. In June 2011, the FOT transitioned from around-the-clock support to a single, staffed shift operating Monday through Friday. On the off-shifts and weekends, a highly robust, autonomous operation system commands and



(Above) Four large, flexible solar-array panels that rolled up like window shades originally provided power to the observatory. Shown on a water table during prelaunch deployment testing, this original design was replaced in Servicing Mission 3B by rigid panels that are less susceptible to twisting caused by the extreme temperature variations they experience in orbit. Although 45 percent smaller than their predecessors, they produce 25 percent more power and reduce the amount of atmospheric drag on the spacecraft. (Left) Astronauts Richard Linnehan (partially visible on the end of Columbia*'s robotic arm) and John Grunsfeld (center frame) work to install a new, rigid array.*

monitors the satellite. FOT members and other knowledgeable systems engineers are notified via cell phone and e-mail if the autonomous system detects any unusual conditions aboard the observatory.

Hubble's electrical power comes from sunlight. Flanking the telescope's body are two thin, 25-foot-long solar arrays, mounted like wings and rotated to point toward the Sun. Each is covered with solar cells that convert the Sun's energy into electricity. Astronauts have replaced the solar arrays twice to supply more power and improve the mechanical stability of the spacecraft. The present arrays are rigid panels of gallium-arsenide cells that were originally designed for commercial communications satellites. They generate approximately 5,700 watts of power and are about 30 percent more efficient in converting sunlight to electricity than the prior arrays.

Batteries are used to allow the telescope to operate while in Earth's shadow, approximately 36 minutes out of each 97-minute orbit. When fully charged, *Hubble*'s six nickel-hydrogen batteries contain enough energy to sustain the telescope in its normal science operations mode for 7½ hours, or five orbits. This is approximately the same amount of charge as carried by 12 typical car batteries. Through careful management of their charge rate and depth of discharge, *Hubble*'s initial set of batteries lasted more than 19 years. After experiencing more than 100,000 charge/discharge cycles, they were replaced with six new batteries in May 2009.

Hubble employs a suite of special devices that work together to maneuver the telescope and keep it aimed precisely on target. Three fixed-head star trackers, used in conjunction with a star catalog in the onboard computer, inform the telescope of its general orientation. Six small gyroscopes sense the telescope's angular motion and also provide this information to *Hubble*'s central processor. Three Fine Guidance Sensors (FGSs) accomplish the final precise aim of the telescope by locking onto selected "guide stars" that center the desired target into a particular instrument's field of view.

Once "locked on" the guide stars, *Hubble* wobbles off-target no more than 7 milliarcseconds within a 24-hour period. This is equivalent to holding the beam of a laser pointer all day on the face of a dime located 200 miles away. Because of the telescope's remarkable stability, the FGSs are also used to make very precise measurements of the relative positions of stars. This data provides essential information for measuring distances to nearby stars and determining the component masses of binary star systems. Four heavy reaction wheels comprise the maneuvering system. *Hubble* exchanges momentum with these flywheels which—in accordance with the laws of motion—spin one way while *Hubble* spins the other.

Two primary computers control the main functions of the spacecraft. One, a circa-1980 computer with 64 kilobytes of memory, communicates with the instruments. It receives their data and telemetry, checks their operational status, and passes their data to special interface units for transmission to the ground. It also relays commands and timing information sent to the instruments from the ground. The more "modern" main spacecraft computer, an Intel 80486-based machine with 2 megabytes of random-access memory, handles pointing control, power management, radio communication with the ground, and other spacecraft-monitoring functions.

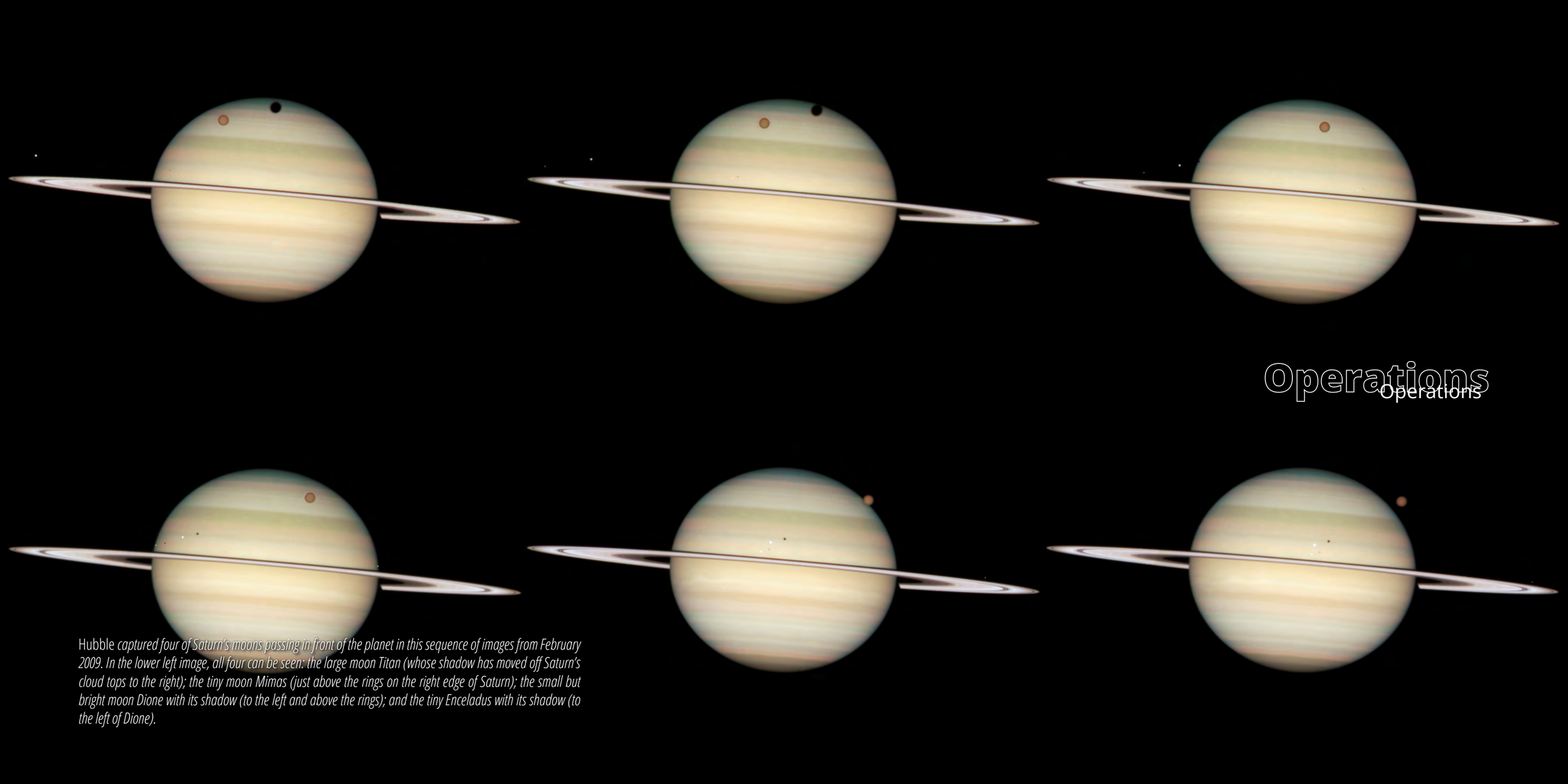
A separate safe-mode computer orients *Hubble* to a power-positive and thermally safe position in the event of a problem. Each science instrument also houses computers and special microprocessors. These are typically Intel 386-class processors and perform such functions as rotating filter wheels, manipulating exposure shutters, maintaining internal temperatures, collecting data, and communicating with the main computers. Not counting redundant (backup) units, there are 12 computers and microprocessors executing flight software on the observatory.

(Above) Disassembled for illustration, each of Hubble*'s gyroscopes measures the spacecraft's rate of motion about a particular axis—information that is forwarded to the spacecraft's pointing control system. The gyroscopic action of the devices is achieved by a wheel inside each gyro that spins at a constant rate of 19,200 rpm on gas bearings. This wheel is mounted in a sealed cylinder that floats in a thick fluid. Electricity is carried to the motor by thin wires, each approximately the size of a human hair, that are immersed in the fluid. Electronics within the gyro detect very small movements of the axis of the wheel. (Right) The gyros are packed in pairs inside boxes called rate sensor units.*

The main engineering computer on Hubble *was upgraded in 1999 during Servicing Mission 3A to an Intel 80486 processor. This computer executes stored commands; formats engineering status data; performs computations to maneuver, point, and stabilize* Hubble*; turns the solar arrays to the Sun; commands the high-gain antennas; and evaluates the health of the spacecraft.*

Hubble's long lifetime and numerous scientific accomplishments are a testimony to how well the telescope was designed, integrated, maintained, and upgraded throughout the years. Many of its discoveries would have been impossible to achieve with the science instruments installed at launch. *Hubble*'s design serves as a prototype for the next generation of space or lunar-based telescopes, pioneering the way for serviceable observatories in the future.

Hubble*'s three original data recorders were mechanical tape recorders with many moving parts that wear out with use. (Left) Two of the three tape recorders were replaced during servicing missions with digital solid-state recorders (SSRs). The digital SSRs have no moving parts or tape to break and can each store more than 12 gigabits of data, 10 times the capacity of the tape recorders they replaced. (Right) Astronaut John Grunsfeld maneuvers to install a solid-state recorder during* Hubble *Servicing Mission 3A in December 1999.*



Operations

Operations

Hubble *captured four of Saturn's moons passing in front of the planet in this sequence of images from February 2009. In the lower left image, all four can be seen: the large moon Titan (whose shadow has moved off Saturn's cloud tops to the right); the tiny moon Mimas (just above the rings on the right edge of Saturn); the small but bright moon Dione with its shadow (to the left and above the rings); and the tiny Enceladus with its shadow (to the left of Dione).*

Operations

Hubble is an orbiting astronomical observatory. Its routine operation requires a mix of knowledgeable personnel similar to those found supporting many ground-based observatories. In the simplest sense, scientists plan the observations and analyze the science data taken while engineers and operations staff enable the systems that make the data collection possible. These functions are sometimes distinguished as science operations and mission operations.

For *Hubble*, the science operations function is conducted from the Space Telescope Science Institute (or Institute), located on the Homewood campus of The Johns Hopkins University in Baltimore, Maryland. Mission operations work is performed from NASA's Goddard Space Flight Center (Goddard) in Greenbelt, Maryland, about 30 miles south of the Institute.

Both science operations and mission operations are far more difficult for *Hubble* than those at ground-based observatories. The chief challenge is to command and retrieve data from *Hubble* as it circles the Earth every 96 minutes at more than 17,000 miles per hour. Other difficulties include keeping its optical components stable in the extreme thermal environment of space and protecting its electronics from space radiation. The close proximity of the Earth and its minute-by-minute potential to block *Hubble*'s view also makes it a challenge to schedule the telescope efficiently.

Awarding Telescope Time

The process of observing with *Hubble* begins with an annual *Call for Proposals* issued by the Institute to the astronomical community via the Web. Astronomers worldwide are given approximately two months to submit a phase-one proposal that makes a scientific case for using the telescope. Scientists typically request the amount of telescope time they desire in orbits, each 96 minutes long. Longer observations require a more compelling justification since only a limited number of orbits are available. Winning proposals must be well reasoned

The Flight Operations Team monitors the health and safety of the spacecraft in the Space Telescope Operations Control Center at the Goddard Space Flight Center. Activities also include sending command loads to the spacecraft, monitoring their execution, and arranging for transmission of science and engineering data to the ground.

Hubble *operations entered a new phase in 2011 with the automation of many of the spacecraft's routine functions. Flight controllers now work a single shift, Monday through Friday. During off-hours and weekends, computers command the telescope and dump its data recorders. E-mail alerts, phone messages, and telemetry access via hand-held devices keep the operations team informed of* Hubble*'s status.*

and address a significant astronomical question or issue. Potential users must also show that they can only accomplish their observations with *Hubble*'s unique capabilities and cannot achieve similar results with a ground-based observatory.

The Institute assembles a time allocation committee, comprising experts from the astronomical community, to determine which proposals will receive observing time. The committee is subdivided into panels that review the proposals submitted within a particular astronomical category. Sample categories include stellar populations, solar system objects, and cosmology. The committee organizers take care to safeguard the process from conflicts of interest, as many of the panel members are likely to have submitted their own proposals.

Proposals are further identified as *general observer*, which range in size from a single orbit to several hundred, or *snapshot*, which require only 45 minutes or less of telescope time. Snapshots are used to fill in gaps within *Hubble*'s observing schedule that cannot be filled by general observer programs. Once the committee has reviewed the proposals and voted on them, it provides a recommended list to the Institute director for final approval.

Planning the Observations

Researchers who are awarded telescope time based on the scientific merit of their phase-one proposal must submit a phase-two proposal that specifies the many details necessary for the implementation and scheduling of his or her observations. These details include such items as precise target locations and the wavelengths of any optical filters required. Once an observation has occurred, the data is marked as proprietary within the Institute computer systems for 12 months. This protocol allows observers time to analyze the data and publish their results. At the end of this proprietary-data-rights period, the data is made available to the rest of the astronomical community via the *Hubble* data archive.

Along with their phase-two proposal, observers can also apply for a financial grant to help them process and analyze their observations. These grant requests are reviewed by an independent financial review committee, which then makes recommendations to the Institute director for funding. Grant funds are also available for researchers who submit phase-one proposals to analyze non-proprietary *Hubble* data already archived. The financial committee evaluates these requests as well.

Up to 10 percent of *Hubble*'s time is reserved as discretionary time and is allocated by the Institute director. Astronomers can apply to use these orbits any time during the course of the year. Discretionary time is typically awarded for the study of unpredictable phenomena such as new supernovas or the appearance of a new comet. Historically, directors have allocated large percentages of this time to special programs that are too big to be approved for any one astronomy team. For example, the observation of the *Hubble* Deep Field (1996) and *Hubble* Ultra Deep Field (2004) both used director's discretionary time.

Scheduling the Telescope

The Institute creates a long-range schedule to order the diverse collection of observations awarded telescope time as efficiently as possible. This task is complicated because the telescope cannot be pointed too close to bright objects like the sunlit side of Earth, the Sun, and the Moon. Adding to the difficulty, each astronomical target can

only be seen during certain months of the year; some instruments cannot operate in the high space-radiation areas of *Hubble*'s orbit; and the instruments regularly need to be calibrated. Preparing for an observation also involves selecting guide stars to stabilize the telescope's pointing and center the target in the instrument's field of view. The selection is done automatically by the Institute's computers, which choose two stars per pointing from a catalog of almost a billion stars.

A weekly, short-term schedule is created from the long-range plan. This schedule is translated into detailed instructions for both the telescope and its instruments to perform the observations and calibrations for the week. From this information, daily command loads are then sent from the Institute to Goddard to be uplinked to *Hubble*.

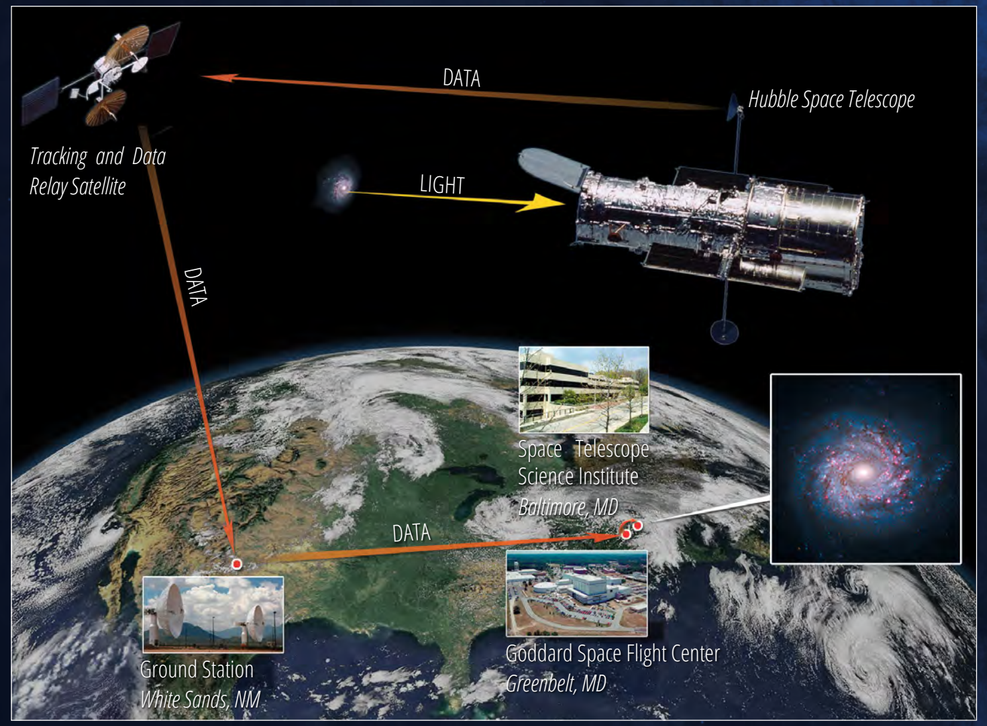
Mission Operations

At Goddard, a number of groups conduct mission operations for the observatory. The Flight Operations Team (FOT), along with a group of spacecraft engineers, maintain the health and safety of the observatory. Together, they monitor *Hubble*'s telemetry and check the spacecraft's subsystems for correct daily performance and longer-term trends.

Other personnel are responsible for modifying *Hubble*'s flight software. Extensive software testing facilities and simulators assure that any changes to this code are done safely. Programmers, system administrators, hardware field engineers, database administrators, and testers all coordinate activities at Goddard to keep the mission operations systems functioning reliably. Similar groups at the Institute ensure the integrity of the science operations systems.

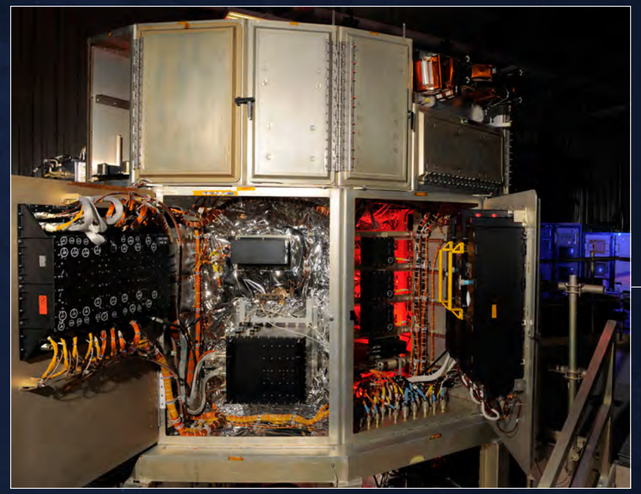
Communication with *Hubble* is accomplished via NASA's Tracking and Data Relay Satellite System (TDRSS). The TDRSS's satellites provide nearly continuous communications coverage with *Hubble*. FOT members uplink the command loads from the Institute into *Hubble*'s main onboard computer, which then executes the commands at

Operating Hubble *requires a dedicated staff of knowledgeable and detail-oriented personnel. Here, a flight software engineer reviews a flow diagram of the on-board computer code that calculates and corrects for small signal variations from* Hubble*'s six, sensitive, rate-sensing gyroscopes. These signal variations increase with time, requiring periodic adjustments to the flight software algorithms within the pointing control system of the telescope.*



The Hubble Space Telescope *uses NASA's Tracking and Data Relay Satellite System and its ground station to transfer data to* Hubble*'s control center at Goddard. The scientific data is then transmitted to the Space Telescope Science Institute, where it is processed and distributed to the astronomical community.*

prescribed times to maneuver the telescope and take observations. Solid-state data recorders store the science data on the spacecraft. FOT members have the responsibility of managing the content of these recorders and periodically transmitting the data to TDRSS's ground terminal at White Sands, New Mexico. From there, the data is sent to Goddard to ensure its completeness and accuracy. Goddard then sends the data to the Institute for processing, calibration, and archiving.



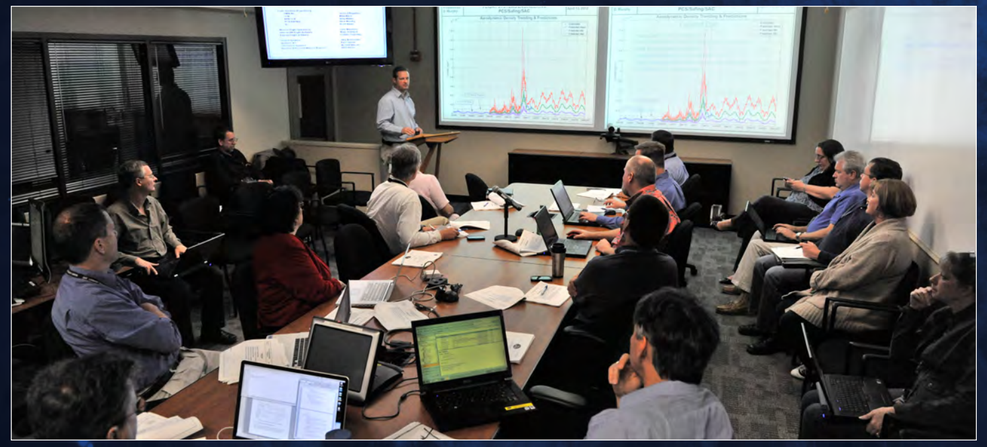
The Vehicle Electrical Systems Test (VEST) unit at Goddard is a high-fidelity Hubble *simulator comprising spare flight components as well as various boxes that emulate spacecraft subsystems and instruments. The VEST is used to diagnose spacecraft anomalies as well as to validate new operating procedures and flight software.*

The Space Telescope Operations Control Center at Goddard is staffed by the FOT Monday through Friday on a single, eight-hour shift. A robust automated-operations system conducts routine activities after-hours and on weekends. It performs routine commanding, monitors telemetry from the spacecraft, and alerts appropriate personnel via phone calls, text messages, and e-mails when anomalies occur.

Hubble generates approximately 600 gigabytes of new science data each month. Astronomers, in turn, typically download 3 to 5 terabytes of data monthly from this growing archive. By the end of 2011, *Hubble* data had been used to publish more than 10,000 peer-reviewed scientific papers, a number that has continued to grow by approximately three per day.

One Astronomer's Story

Images and spectra from *Hubble* are always scientifically valuable, but not necessarily beautiful. The public's ability to connect with the telescope, however, depends upon producing aesthetically powerful images. Because such images are not always generated during the normal course of scientific analysis, a dedicated project called *Hubble* Heritage was created in 1998. In fact, the *Hubble* Heritage group has produced a significant percentage of the most popular images in the telescope's online catalog.



(Above) Technical status meetings are held monthly with flight operations, ground systems, flight software, and system engineering personnel to review the observatory's performance and discuss any issues regarding the many flight and ground components of the mission. (Below) Similarly, NASA project management personnel meet regularly with the Space Telescope Science Institute staff to review the performance of the instruments, gauge the effectiveness of science operations, and survey the latest astronomical results. The information is used to prioritize future work and to keep the observatory operating as safely and efficiently as possible.

In 2012, *Hubble* Heritage Principal Investigator Zolt Levay proposed a spectacular planetary nebula, NGC 5189, as one of three targets for the project. NGC 5189, a star in a late stage of evolution, is ejecting its outer layers in a dramatic fashion. It exhibits a remarkable spiral structure that is unusual for this type of object. Excellent, ground-based images showed intriguing details of this complex structure, which made it a good candidate for *Hubble*, whose finer resolution could reveal even more detail. Furthermore, the crisp and clear images *Hubble* was expected to obtain would be useful, along with analysis of the ground-based data, for developing a three-dimensional visualization of the object.

On May 2, 2012, Levay and the Heritage team submitted a proposal for director's discretionary time. Heritage observations were requested through the director's discretionary process rather than the usual science proposal process because the program's goal is primarily outreach. Although it is historically unusual for large observatories to allocate telescope resources for outreach, several Institute directors have generously approved Heritage proposals for a small fraction of the available *Hubble* orbits. In addition to producing images for public outreach, these datasets have research value and are available for scientific analysis.

Several other factors were involved in the choice of NGC 5189 besides its spectacular nature. First, it is bright enough to observe with the relatively few orbits available to the Heritage team; second, it fits neatly in *Hubble*'s field of view; and third, the narrow-band filters available with Wide Field Camera 3 are especially well suited to imaging planetary nebulas.

Levay's phase-one discretionary time proposal was accepted on May 18, 2012. Then he and the Heritage team submitted a phase-two proposal that contained specifics on how the observations would be carried out. After these details were finalized and their technical feasibility was confirmed, the observation was scheduled.

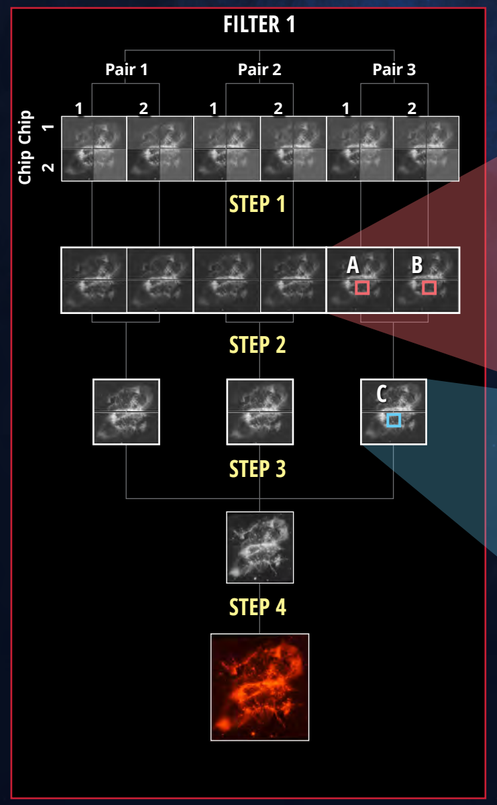
Hubble observed NGC 5189 on July 6, 2012. The view consisted of six orbits and used five filters for a total of 426 minutes of exposure time. While this observation was accomplished in a single pointing during consecutive orbits, this is rarely the case. *Hubble* often moves to an entirely different target, then returns later to complete an observation, sometimes building a mosaic of several adjacent fields.

A planetary nebula emits light in discrete colors produced by particular chemical elements in specific physical conditions. Color filters used in combination with the telescope's black-and-white detectors isolate these colors

Creating a Color Image of NGC 5189 from Hubble Data

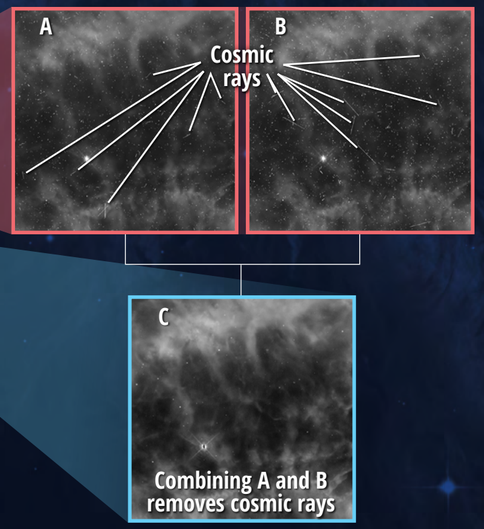
Data from each of Hubble's instruments is processed differently, but the simplified procedure outlined here is typical for images taken with Wide Field Camera 3. The camera only records black and white images. By taking exposures through multiple color filters, scientists create a composite color image by establishing the relative brightness of the target in each color filter.

The camera's detector consists of two adjacent computer chips separated by a small gap. Six individual exposures (three sets of two) are taken through red, green, and blue filters. Between each pair of exposures, the telescope moves very slightly, or dithers, so that the image falls upon different pixels in the detector. This permits (Step 1) the identification and removal of features created by pixel-to-pixel and chip-to-chip differences within the detector. Combining the pair of exposures taken at each dither location then permits (Step 2) identification and removal of streaks in the images caused by cosmic rays. Magnified views show image pair A and B forming a third image C that is free of these streaks. The three images are then combined (Step 3) to further minimize any distortions introduced by the optics. Color information is then added for the given filter (Step 4) and the three color images combined into a full-color composite (Step 5). See page 51.



STEP 1. Data from the archive is calibrated so as to remove artifacts caused by the physical and electrical characteristics of the detector.

STEP 2. Cosmic rays are removed by combining two, identical exposures and subtracting the differences.



STEP 3. Three images taken at different, overlapping positions are combined to fill in the gaps between the detector's two computer chips and to remove any residual image distortions.

STEP 4. Color is applied to the black-and-white image.

STEP 5. Three color images are combined into a full-color, composite image.

from the wider spectrum. A final composite color image is later constructed by combining these together. The relative brightness of the light recorded through each of the various filters determines the final color in each pixel of the image. (See graphic on page 48.)

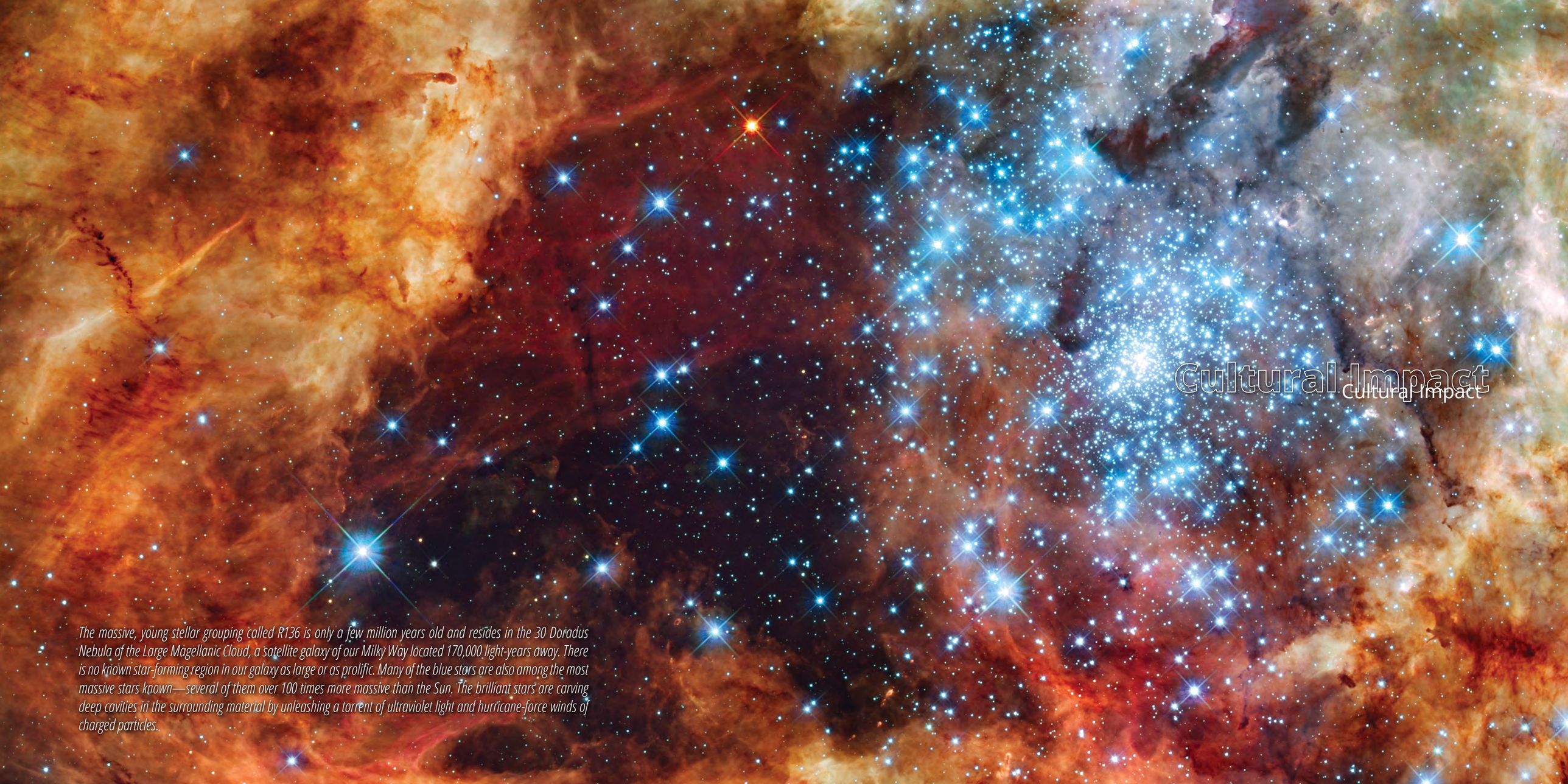
Once *Hubble* took the observation and the data was stored in the archive, Levay and the Heritage team received an e-mail notification that the image was available. The routine data processing it received included calibration, geometric correction, image combination to fill the gap between the camera's detector chips, and cosmic ray subtraction. Heritage team members processed the data further to produce a single image for each filter and then created the composite color image.

In collaboration with the news office at the Institute, the Heritage team released the image of NGC 5189 to the public as a special holiday image on December 18, 2012.

Hubble observations differ widely in their complexity. The steps taken to produce the color image of NGC 5189 were relatively simple. They did not involve tracking a moving object, like a planet or comet. They also did not require stitching together images of a target too large to fit within a single field of view, coordinating the observation with another observatory, or rolling the spacecraft so that light entered at a particular angle (as required for *Hubble*'s spectrographs).

Though regularly performed, these additional steps require that operations personnel employ an even greater attention to detail than normal to ensure that no errors are made and that the observatory remains safe and productive. *Hubble*'s caretakers are doing everything possible to keep the observatory fully operational for as long as the scientific instruments can advance our understanding of the universe.

Planetary nebulas form around medium-sized stars (like the Sun) during a brief stage near the end of their lives. During this stage, the dying star expels a large portion of its outer gaseous envelope. This material is then ionized by intense ultraviolet radiation released from the stellar remnant, causing the gases to radiate. This planetary nebula, NGC 5189, is located a few thousand light-years away and can be found in the small, southern constellation known as Musca.



Cultural Impact

Cultural Impact

The massive, young stellar grouping called R136 is only a few million years old and resides in the 30 Doradus Nebula of the Large Magellanic Cloud, a satellite galaxy of our Milky Way located 170,000 light-years away. There is no known star-forming region in our galaxy as large or as prolific. Many of the blue stars are also among the most massive stars known—several of them over 100 times more massive than the Sun. The brilliant stars are carving deep cavities in the surrounding material by unleashing a torrent of ultraviolet light and hurricane-force winds of charged particles.

Dr. Adam G. Riess received the Nobel Prize in Physics from His Majesty King Carl XVI Gustaf of Sweden at the Nobel Prize Award Ceremony in Stockholm on December 10, 2011. Dr. Riess and his colleagues received the award for their leadership in discovering that the expansion rate of the universe was accelerating, a phenomenon attributed to a mysterious, unexplained "dark energy." Dr. Riess' team used Hubble *data to make the discovery. (Photo credit: © The Nobel Foundation/Frida Westholm)*

Cultural Impact

Hubble's discoveries and memorable photos have reinvigorated the public's interest in astronomy and have made the universe more accessible to citizens. The best photos have become cultural icons that appear regularly on book covers, on albums, and in popular science-fiction movies. *Hubble* images have even been incorporated into ecclesiastical stained-glass windows.

Hubble has ushered in a new age of science exploration. Science literacy has risen 10 percentage points since astronauts repaired *Hubble* in 1993. Though this cannot be attributed to *Hubble* exclusively, the accomplishments of the space telescope have certainly contributed to elevating public awareness of scientific research.

Coincident with *Hubble*'s repair in the early 1990s was the rapid growth of the Internet and high-speed data transmission into households. The immediacy of the Internet made *Hubble* images easily accessible to a broad range of society. This allowed teachers, parents, and children alike to track the preparation and execution of the *Hubble* servicing missions and become familiar with the telescope, its instrumentation, and its accomplishments.

With this awareness has come inspiration. School children write, color, and speak about the beauty and mystery of the universe as revealed by *Hubble*. The telescope became so beloved that when its last servicing mission was recommended for cancellation, school children wrote letters to Congress and collected money to "save *Hubble*."

The *Hubble Space Telescope* also permeates educational material. If one compares an astronomy textbook from the late 1980s to a textbook published today, the differences are extraordinary. Nearly every chapter of contemporary textbooks contains *Hubble* pictures that are seminal to the topics at hand: supermassive black

The Nobel medal bears the image of Alfred Nobel (1833–1896), the Swedish scientist and inventor whose large financial gift established the coveted prizes.

Edwin Hubble, for whom the Hubble Space Telescope *is named, was one of the leading astronomers of the twentieth century. His discovery in the 1920s that countless galaxies exist beyond our own Milky Way galaxy revolutionized our understanding of the universe. Perhaps Hubble's most notable contribution, however, was his observation that the farther apart galaxies are from each other, the faster they move away from one another. Based on this discovery, Hubble concluded that the universe expands uniformly. Several scientists had also posed this idea based on Einstein's general theory of relativity, but Hubble's data, published in 1929, helped convince the scientific community. In 2000, the United States Postal Service commemorated Hubble and his namesake — the* Hubble Space Telescope *— with a commemorative issue of stamps.*

Hubble*'s data inspires both art and science around the globe. Here at New York City's American Museum of Natural History, spectra of distant galaxies taken by* Hubble *were projected on the Hayden Sphere within the Rose Center for Earth and Space. Similar outdoor exhibits appeared in Baltimore, Maryland, and Venice, Italy. (Photo credit: © 2011 AMNH/D. Finnin)*

holes, stellar evolution, planet impacts, cosmology, and galaxy classification, to name a few. The same is true for online references such as Wikipedia that now are replete with *Hubble* photos illustrating astronomical discoveries.

During the years of *Hubble*'s operation, there have been other major government-funded science activities. But the *Hubble* project has managed to push beyond the important but narrow mission of academic inquiry to captivate the world in the adventure of discovery with its overpowering images that both challenge and inspire. *Hubble* has essentially become the "people's telescope" and now carries the public as co-investigators as it continues unveiling the mysteries and wonders of the universe.

Queen Elizabeth II and Prince Philip, the Duke of Edinburgh, receive a framed photograph of the Hubble Space Telescope *from Maryland's Senator Barbara Milkulski and Representative Steny Hoyer during a visit to the Goddard Space Flight Center in May 2007.*

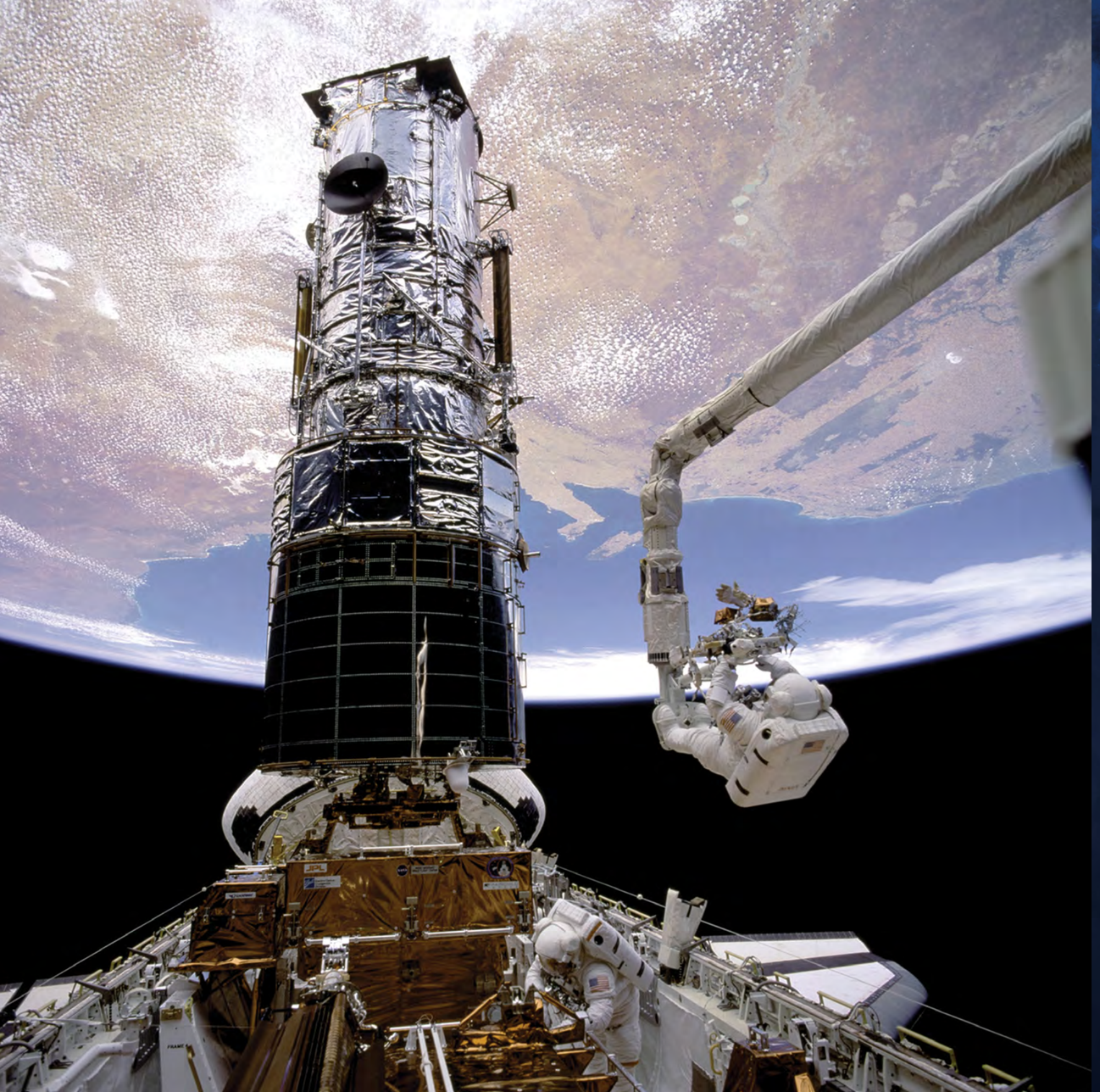
In October 2010, the Istituto Veneto di Scienze, Lettere ed Arti in Venice, Italy featured an exhibition entitled The Hubble Space Telescope: Twenty Years at the Frontier of Science. Displayed in the beautiful and historic Palazzo Loredan, the exhibits included many breathtaking Hubble *photos taken over the years, as well as artifacts from the telescope and tools used by astronauts in the missions to repair and upgrade it. (Photo credit: Bob Fosbury, ESA/*Hubble*)*

Among its many honors, Hubble *and its images (left to right) have been featured on NOVA, the most watched documentary series on U.S. public television (Credit: © WGBH Educational Foundation); promoted in a popular book published by the National Geographic Society, similar to other books that document* Hubble*'s history and remarkable images (Credit: © 2008 National Geographic Society); depicted as a Google Doodle (Credit: Google, Inc.); and graced the cover of National Geographic (Credit: © National Geographic Society).*

Acknowledgments

Acknowledgments

This detailed image of the center of the Lagoon Nebula (Messier 8) reveals the intricate structures formed when powerful radiation from young stars interacts with the hydrogen cloud from which they formed. In this color-mapped image, light from glowing hydrogen is colored red; that from glowing ionized nitrogen, green. Background light captured through a yellow filter is colored blue. The bluish, bright area at the upper left of the image is scattered light from a bright star just outside the field of view.



Hubble Credit

Credit for the success of the *Hubble Space Telescope* rightly belongs to an entire "universe" of people and organizations. First and foremost are the citizens of the United States and Europe who have steadfastly supported *Hubble* over the years with their tax dollars and their enthusiasm. As a result, thousands of astronomers from around the world have successfully used the observatory to probe the deepest mysteries of the universe and have shared their discoveries through both professional publications and public outreach. Educators and students worldwide have recognized *Hubble* as an important reason for their knowledge, excitement, and motivation to excel in the fields of science and engineering.

A small cadre of astronauts from NASA and the European Space Agency (ESA) have taken significant personal risk to service *Hubble*, maintaining and upgrading the observatory to keep it at the forefront of astronomical research. Support from dedicated personnel at the Johnson Space Center and Kennedy Space Center made these servicing missions successful. The Science Mission Directorate at NASA Headquarters and the *Hubble Space Telescope* Project Office at NASA's Goddard Space Flight Center have led the *Hubble* program over the years, with major contributions to the observatory—both hardware and people—provided by ESA.

Hubble's highly successful science program has been organized and guided by the Space Telescope Science Institute, operated by the Association of Universities for Research in Astronomy under contract with NASA. Finally, many dedicated NASA employees and dozens of first-class contractor organizations throughout the global aerospace industry have designed, built, and successfully operated *Hubble* and its scientific instruments over a period spanning decades. All these people and organizations should take pride in the achievements described in this publication. Their unified commitment to excellence ultimately forms the basis of *Hubble*'s success.

While astronaut Jeffrey Hoffman worked in the payload bay, astronaut F. Story Musgrave—anchored on the Space Shuttle Endeavour*'s robotic arm—prepared to be elevated to the top of* Hubble *during Servicing Mission 1 (December 1993). They represent just two of the thousands of dedicated professionals from many countries that have made* Hubble *one of the most productive scientific instruments in history.*

Publication Credit

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Astronomers have periodically used Hubble *to integrate many individual images of a single field of view into an extremely long exposure. This one, the Ultra Deep Field, required 800 images for a combined exposure length of a million seconds (11.3 days). In it, nearly 10,000 galaxies were recorded. The area of the sky sampled in this photo is about the size of the period at the end of this sentence viewed from normal reading distance.*

Hubble

An Overview of the Space Telescope

The cluster of galaxies known as Cl 0024+17 is found in the constellation Pisces. Astronomers use clusters like this one to probe the nature of dark matter, a mysterious substance that exerts gravitational force but is otherwise undetectable. Blue streaks seen near the center of Cl 0024+17 are the smeared images of galaxies that are not part of the cluster but are located at a great distance behind it. These distant galaxies appear distorted because their light is being bent and magnified by the powerful intervening gravity of Cl 0024+17—an effect called gravitational lensing. By measuring the extent of the lensing, astronomers can derive the total mass of the cluster and estimate the amount of dark matter it contains.