Hubble Space Telescope

1999
2000

Biennial Report

"Discoveries in basic science drive the engine of technological advance, which keeps raising our national standard living and creates new jobs. One cannot predict the long term effects of scientific discoveries. The U.S. space exploration program has itself spawned new products and new industries ... there at least resides hope for future benefits for our country and for mankind -- and jobs."

Lester Ageloff
Letter to the Editor
Florida Herald-Tribune

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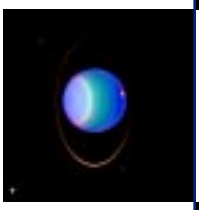
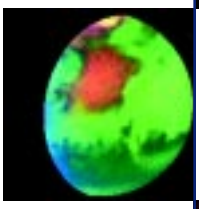




I. A Decade of Excellence

Not since Galileo turned his telescope toward the heavens in 1610 has any event so changed our understanding of the Universe as the Hubble Space Telescope. With its unprecedented power and clarity, Hubble is leading an exciting, new revolution in astronomy and breaking ground in on-orbit servicing.

1. Crewmembers of STS-82; 2. Spiral galaxy captured with the Hubble Space Telescope

Orbiting 370 miles above Earth, Hubble works around the clock to unlock the secrets of our Universe. With its exquisite pointing precision, powerful optics, and state-of-the-art instruments, Hubble provides views of the Universe simply unattainable from ground-based telescopes or other satellites. Hubble is in high demand as astronomers compete for observing time. Only one in six proposals is accepted.

Even when reduced to raw numbers, Hubble's accomplishments are extraordinary. Every day, Hubble archives 3 to 5 gigabytes of data and delivers between 10 and 15 gigabytes to astronomers all over the world. As of July 2000, Hubble has:

- Taken more than 347,000 separate observations.
- Observed more than 30,000 astronomical targets.
- Created a data archive of over 7.7 terabytes (that's like completely filling a PC every day for 10 years).
- Provided data for more than 2,785 scientific papers.
- Traveled about 1.539 billion miles—nearly the distance from Earth to Uranus. HST circles the Earth about every 97 minutes.
- Received more than 93 hours of on-orbit improvements in three successful servicing missions.

Hubble yields images of amazing complexity, diversity and beauty as it unlocks the mysteries of the Universe. In revealing the first clear views of deep space, Hubble helps astronomers understand how galaxies and stars formed in the early Universe. Before Hubble, distances to far-off galaxies were not well known and a great controversy existed over how rapidly the Universe is expanding and how long the expansion has been occurring. The telescope fulfilled its promise to accurately measure the size, rate of expansion, and age of the Universe.

The second decade promises to be as exciting as the first. New, more powerful instruments will be installed on Hubble during the final two servicing missions. The new instruments will be 10 to 20 times more powerful than the existing instruments and they promise to provide new opportunities for scientific discovery.

Hubble Science & Technology: at the Forefront

Although designed in the 1970s and launched in 1990, Hubble is a state-of-the-art, model year 2000 space telescope—thanks to on-orbit servicing. Hubble is the first scientific mission of any kind specifically designed for routine servicing by spacewalking astronauts. Its visionary, modular design allows servicing crews to perform periodic improvements, ensuring that Hubble produces first-class science using cutting-edge technology.

The following scientific and technological achievements are just some of the highlights of Hubble's illustrious career.

- Hubble was the first optical telescope to provide convincing proof of a black hole several billion times the mass of the Sun. Now it is demonstrating that supermassive black holes are at the core of most, if not all, galaxies.
- Hubble cleared up the mystery of quasars, which until recently were among the least understood objects in the Universe. It confirmed that quasars are actually active galactic nuclei in distant galaxies and are powered by black holes.
- Until Hubble, scientists could not determine if mysterious, intense bursts of gamma rays originated in our own galaxy, far across the Universe, or somewhere in between. The telescope traced these bursts to the outskirts of faint, distant galaxies in the early Universe.
- Hubble teamed with ground-based telescopes to observe exploding stars in galaxies whose light was emitted when the Universe was half its present age. The preliminary result, if confirmed, will be one of the most important scientific discoveries of our time—that the expansion of the Universe is accelerating, driven by an unknown force.
- Hubble's unprecedented views of star birth reveal the diverse and complex processes that influence star formation. They show that planet-forming dust disks surrounding young stars are common throughout the galaxy. Hubble was the first telescope to reveal the internal structures of these disks, which suggest the presence of newly formed planets.
- The telescope's exquisite images of dying stars help scientists understand the death process and how it is influenced by each star's specific circumstances. Although many telescopes have observed Supernova 1987A, only Hubble can chronicle the spectacular changes as the blast debris expands over time.
- Hubble provided spectacular views of Comet Shoemaker-Levy/9's collision with Jupiter. These violent explosions served to reinforce how volatile our Universe is and how fragile and tenuous our own existence is on Mother Earth. Hubble also provided the first detailed images of Pluto and its satellite Charon, and new understanding of the atmospheres of Uranus and Neptune.
- Hubble revealed stunning views of the northern and southern lights on Jupiter, Saturn and Ganymede, as well as imagery of the dynamic electrical interactions between Jupiter and its satellite Io.

- Hubble is the first spacecraft designed with handrails, easily replaceable equipment, and other astronaut-friendly features. Three fully successful servicing missions have kept Hubble healthy and updated, and two more missions will take place before the end of Hubble's career.
- The 1993 servicing mission saw the first use of a computer-controlled space tool, the Power Ratchet Tool (PRT). The first cordless power tool in space, the Pistol Grip Tool (PGT), was used to service Hubble in 1997 and 1999.
- Astronauts on the 1999 mission became the first to use the highly efficient Lithium Ion batteries in a space tool. They also installed the first extremely radiation-resistant, Intel-based 486 computer in orbit.
- Hubble is the first spacecraft to use ultraviolet Multi-Anode Microchannel Array (MAMA) detectors, which see in ultraviolet but are blind to sunlight and other visible light. These detectors are part of the Space Telescope Imaging Spectrograph (STIS), which was installed in 1997, and the Advanced Camera for Surveys (ACS), which will become part of Hubble in 2001.
- Hubble innovated a unique pointing and control system, which is extraordinarily stable and precise. It is designed to point to within 0.01 arcsec (an arcsec is the width of a paperclip wire viewed from the distance of two football fields). It holds the telescope in that orientation with 0.007-arcsec stability for up to 24 hours while Hubble orbits the Earth at 17,500 mph. This level of stability and precision is comparable to standing in Washington D.C. and steadily focusing a laser beam on a dime atop the Empire State Building in New York City, approximately 200 miles away.
- Hubble's huge solar arrays, replaced in 1993 and 1997, hold the record for the largest structures ever replaced in orbit.
- The 1997 servicing mission was the first to use magnetic, eddy current shock absorbers in space. This technology was a great success for Hubble and has been employed in commercial applications.
- In 2001, Hubble will employ the first-ever high-tech refrigerator, which will cool and restore life to the now-dormant Near Infrared Camera and Multi-Object Spectrometer (NICMOS). The system is the first space use of a new technology called a Reverse Brayton-Cycle Cryocooler. It is powered by a compressor capable of running at up to 450,000 rpm with a tiny turbine generator turning at up to 300,000 rpm. In 1998, the Hubble program achieved another first by successfully demonstrating the capabilities of this system during the STS-95 mission.

These exciting accomplishments reflect the ingenuity and perseverance of the entire Hubble team, which is dedicated to ensuring the telescope's health and optimal performance well into the 21st Century. With powerful new instruments scheduled for installation, we have every reason to believe the best is yet to come.

II. Hubble and Servicing

Science on the Cutting Edge

Accelerated innovation through human intervention in space is a core concept of Hubble's design. One of the most important features of the Hubble Space Telescope is its ability to be maintained and upgraded on orbit. These human activities allow the observatory to produce the best astronomical data humankind has ever collected over a two-decade period. Hubble's revelations have already rewritten scientific textbooks, putting us on the path of discovering the most intimate secrets of our Universe.

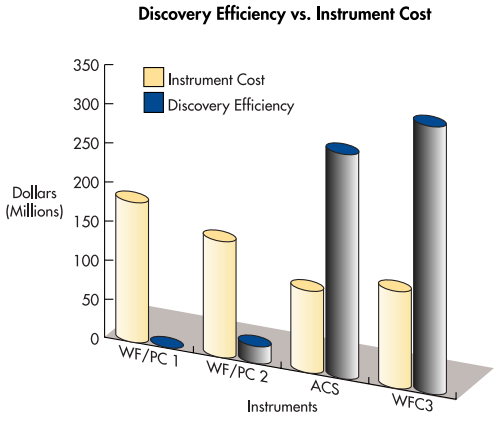
STS-103 spacewalk

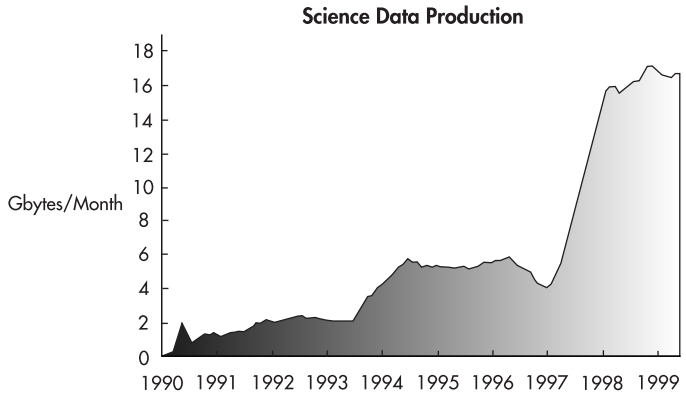
Every few years, a team of astronauts carries a full manifest of new equipment on the Space Shuttle for the ultimate "tune-up" in space. The telescope was being designed as the Space Shuttle was being readied for its first flights. NASA realized that if a shuttle crew could service Hubble, it could be upgraded and maintained indefinitely, representing risk management at its best. So from the beginning, Hubble was designed to be astronaut-friendly. Its modular design allows NASA to equip Hubble with new, state-of-the-art, scientific instruments every few years, giving the telescope exciting new capabilities with each servicing mission. Each new instrument increases Hubble's scientific power by a factor of 10 or greater.

Instrument Cost: The development cost of the instrument up to the end of the test period in space.

Discovery Efficiency: The figure-of-merit that estimates how well an imaging instrument can make new discoveries

In addition to science upgrades, the servicing missions permit astronauts to replace limited-life components with systems incorporating the latest technology. This further improves telescope performance and ensures continued mission success. With each servicing mission, Hubble essentially becomes a new state-of-the-art observatory. This is achieved at a fraction of what it costs to build a series of space observatories "from scratch." The science instruments developed are 10 to 20 times more powerful and cost half as much as the earlier science instruments.





Hubble Servicing Mission-3A: Now Better Than Ever

The Hubble Space Telescope is alive and well and back on duty after a successful December 1999 Servicing Mission (SM3A). "Better than new," is how Dr. Ed Weiler, NASA Associate Administrator for Space Science, described Hubble. To prove it, NASA released two stunning images Hubble took just two weeks after Discovery's Christmas-time service call.

NASA decided to split Hubble's Third Servicing Mission (SM3) into two parts, SM3A and SM3B, after the third of Hubble's six gyroscopes failed. In accordance with NASA's flight rules, a "call-up" mission was quickly developed and approved. The second part of the mission, SM3B, is scheduled for late 2001.

What was originally conceived as a mission of preventive maintenance became more urgent on November 13, 1999 when the fourth of six gyros failed and Hubble temporarily closed its eyes on the Universe. Unable to conduct science without three working gyros, Hubble entered a state of dormancy called safe mode. Essentially, Hubble "went to sleep" while it waited for help.

The crew of STS-103 preparing to board Space Shuttle Discovery.

The Hubble team developed and executed the SM3A mission in record time, leaving the telescope far more fit and capable than ever before. SM3A represented the first time that NASA ever planned and executed a complex mission in only seven months. The new, improved, and upgraded equipment included six fresh gyroscopes, six battery voltage/temperature improvement kits, a faster, more powerful main computer, a next-generation solid state data recorder, a new transmitter, an enhanced fine guidance sensor, and new insulation.

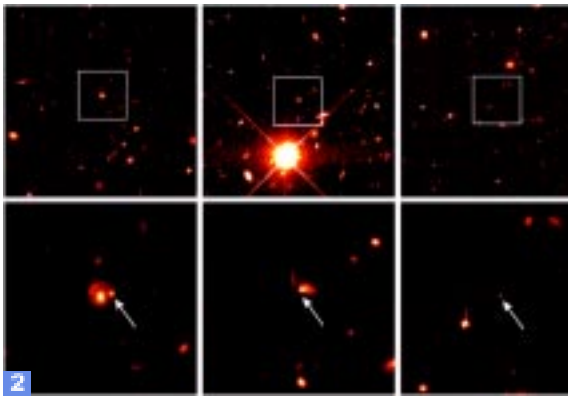
As NASA Administrator Dan Goldin told the crew, "Everyone on this planet is going to share the fruits of what you have done. You've done all of us proud."

III. The 10 Greatest Hubble Discoveries of the Past Decade

With its extremely sensitive detectors and precise optics, the Hubble Space Telescope yields images of awesome complexity, diversity, and beauty. Its vision, which ranges from ultraviolet to near-infrared, provides explanations to long-pondered astronomical puzzles. Hubble also delivers unimagined surprises and raises at least as many new questions as it answers. With each new instrument installed during its periodic servicing missions, Hubble's capabilities grow tenfold. What follows is a description of Hubble's greatest accomplishments over the past decade.

Distant Galaxies and Galaxy Evolution

Before Hubble, little was known about galaxies outside our immediate cosmic neighborhood. Hubble's powerful instruments allow scientists to peer deep into space, to a time when our Universe was very young. Providing the first clear view of deep space, Hubble helps astronomers understand the evolution of galaxies and the rate of star formation in the early Universe. The telescope reveals that the early Universe was populated by structures that were much smaller and more irregularly shaped than galaxies in the modern Universe. These smaller structures, made up of young stars and primordial gases, are believed to be the building blocks from which the more familiar spiral and elliptical galaxies formed. (Figure 1)



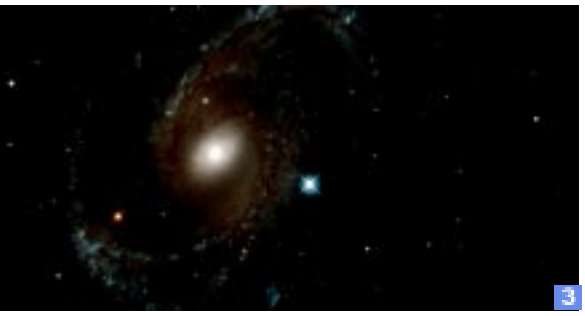
1. The Hubble Deep Field. **2.** Three distant supernovae.

Our Accelerating Universe

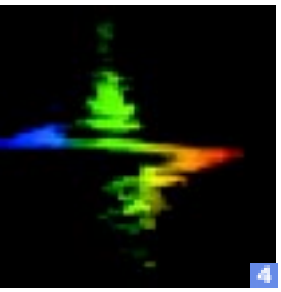
Hubble teamed with ground-based telescopes to observe supernovae in galaxies whose light was emitted when the Universe was half its present age. Only Hubble could accurately measure the brightnesses of the most distant supernovae in the sample. From these measurements, astronomers were able to accurately calculate the galaxies' distances. By combining these distances with the rate at which the galaxies were receding, astronomers determined the rate at which the Universe itself was expanding far back in time. The result was remarkable, providing the first tentative clue that the expansion of the Universe is accelerating—driven by an unknown repulsive "force" strong enough to overcome gravity. Einstein anticipated this possibility by adding a "cosmological constant" to his equations of general relativity. In the next few years Hubble will lead the way by extending these measurements even farther across the Universe and farther back in time. (Figure 2)

Measuring the Universe

Before Hubble, distances to far-off galaxies were not well known, and a great controversy existed over how rapidly the Universe is expanding and how long the expansion has been occurring. Hubble fulfilled its promise to accurately measure the size, rate of expansion and age of the Universe. (Figure 3)

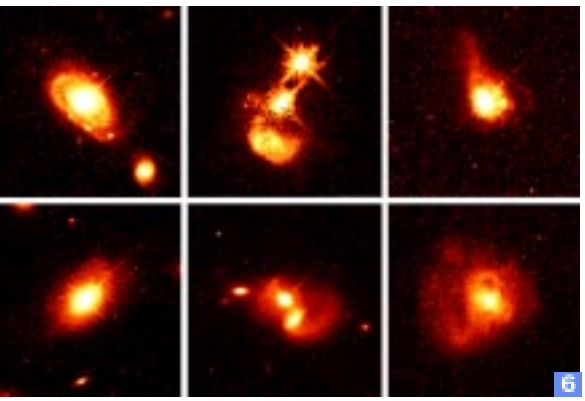


Hubble was the first telescope capable of resolving the "standard candle" Cepheid variable stars and using them to obtain very accurate distances to a large number of moderately distant galaxies. Astronomers used these measurements to recalibrate other standard distance indicators by which they measure galaxies at much greater distances. These calculations resulted in a much more accurate measurement of the rate at which the Universe is expanding (the Hubble Constant) and a determination that the Universe is younger than many astronomers had believed it to be. Before Hubble, scientists placed the age of the Universe at anywhere between 10 and 20 billion years; now they agree that approximately 12 to 15 billion years have elapsed since the Big Bang.



Confirming Supermassive Black Holes

Prior to Hubble's launch, ground-based telescopes hinted at the existence of large concentrations of mass at the very centers of galaxies. Although astronomers suspected these might be the massive black holes predicted theoretically as early as the 1930s, no earthbound optical telescopes could resolve these galaxy centers. Hubble was the first optical telescope capable of probing deeply into the center of a galaxy. It provided the first convincing proof of a black hole several billion times the mass of the Sun. With a "demographic" survey of central black holes now underway, Hubble is demonstrating that supermassive black holes are at the core of most—or perhaps all—galaxies. Ultimately, Hubble will help explain the role these "monsters" play in the formation and evolution of galaxies. (Figures 4 & 5)



3. Spiral galaxy NGC 4603, the most distant galaxy in which Cepheid variables have been found. **4.** The signature of a black hole in the center of galaxy M84. **5.** Massive black hole at the heart of active galaxy M87. **6.** Quasars at the center of a normal spiral galaxy.

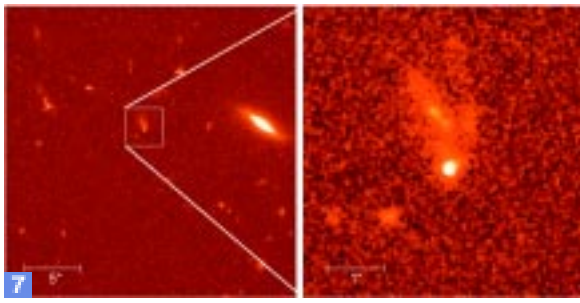
The Nature of Quasars

When quasi-stellar radio sources, commonly known as quasars, were discovered in the 1960s, they were recognized as the most distant and energetic objects known in the Universe. They were also the least understood. Hubble has cleared up much of the mystery surrounding quasars, confirming that they are very distant, active, galactic nuclei in the early universe, undergoing especially intense outbursts of activity, powered by black holes. (Figure 6)

Hubble also reveals that a variety of different types of galaxies play host to quasars. Scientists were surprised to learn that a large portion of these quasar-hosting galaxies are colliding and merging with other galaxies. Galaxy collisions, which Hubble determined were common in the early Universe, may provide the extra "fuel" to feed a host galaxy's central black hole and generate a quasar's enormous energy output.

The Origin of Gamma Ray Bursts

Military satellites first detected intense, mysterious bursts of highly energetic gamma radiation from unknown cosmic sources. Later, the Compton Gamma Ray Observatory (GRO) observed thousands of these bursts and found them to be uniformly distributed over the sky. But the source of these bursts remained a mystery, and scientists could not determine if they originated in our own galaxy, far across the Universe, or somewhere in between.

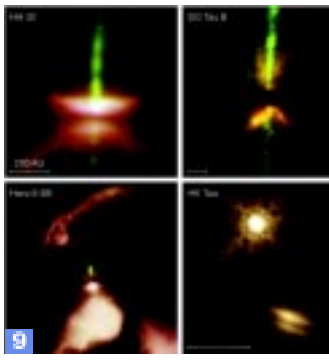


7. The most famous of all planetary nebulae: the Ring Nebula (M57). **8.** Towers of sculpted gas in the Eagle Nebula. **9.** Hubble sees disks around young stars.

A joint Italian-Dutch satellite called Beppo-Sax was designed to spot gamma ray bursts very quickly and to locate their positions accurately, so that other telescopes could be trained on them while the bursts were still bright. The Hubble Space Telescope's exquisite resolution and sensitivity allowed astronomers to locate the sources of the gamma ray bursts in faint, distant galaxies at random distances from their centers. By following the sources to very faint levels, Hubble provided important information about the stellar "catastrophes" that produce these extraordinarily intense and rapid bursts of energy. (Figure 7)

The Birth of Stars

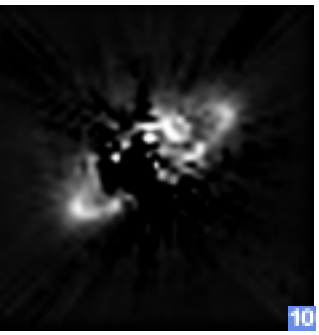
Hubble's resolution and sensitivity allow unprecedented views of the diverse and complex processes of star formation. The telescope captures collisions of galaxies, which stimulate the birth of large populations of young, massive stars and star clusters. Hubble also observes that intense radiation from a massive star can compress interstellar gas and trigger the formation of smaller stars nearby. In supernovae explosions, Hubble views radiation and ejected material that enrich and compress the interstellar gas and dust from which new stars can form. The telescope shows that in large, dense clouds of molecular hydrogen and dust, radiation from nearby hot stars limits the masses of forming stars by eroding away material. Hubble also confirms that a star's formation always seems to be governed by an accretion disk of material falling onto the protostar and by bipolar jets carrying material away from the "construction site." (Figures 8 & 9)



The Formation of Planets

For centuries, astronomers have believed that a disk of dust was the precursor to our own solar system, providing the raw material from which the planets were constructed. Before Hubble, infrared satellites inferred the presence of dust disks around a small number of young stars. One such disk, around Beta Pictoris, had been directly imaged with a ground-based, coronagraphic instrument. (Figures 10 & 11)

The Hubble Space Telescope revolutionized observational astronomy by revealing the abundance of such disks. Hubble finds that about half the young stars in the Orion Nebula are surrounded by gas and dust structures, many of which are clearly disks. High-resolution, near-infrared Hubble images of other star-forming regions show protoplanetary disks forming and evolving. These disks, which appear to be common throughout our galaxy, contain enough material to form entire planetary systems equivalent to our solar system. For the first time in history, Hubble revealed the internal structures of protoplanetary disks and of the debris left behind by prior planet formation. Thus, Hubble has opened up the empirical study of the structure and evolution of protoplanetary systems.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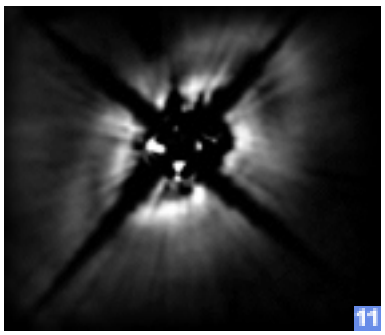
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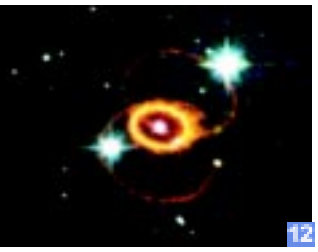
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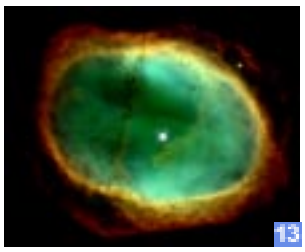
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10. Dust ring around star offers new clues into planet formation.
11. Gap in stellar dust disk may be swept out by planet.
12. Supernova 1987A
13. The "Eight-Burst" or the "Southern Ring" Nebula

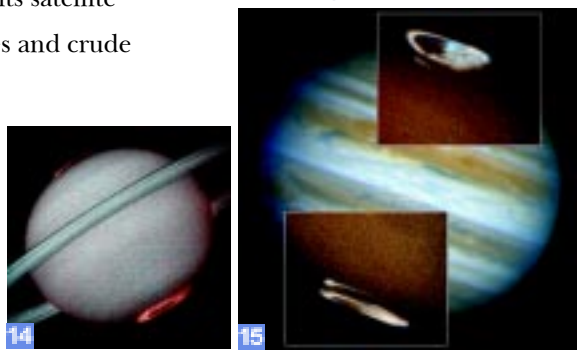
The Death of Stars

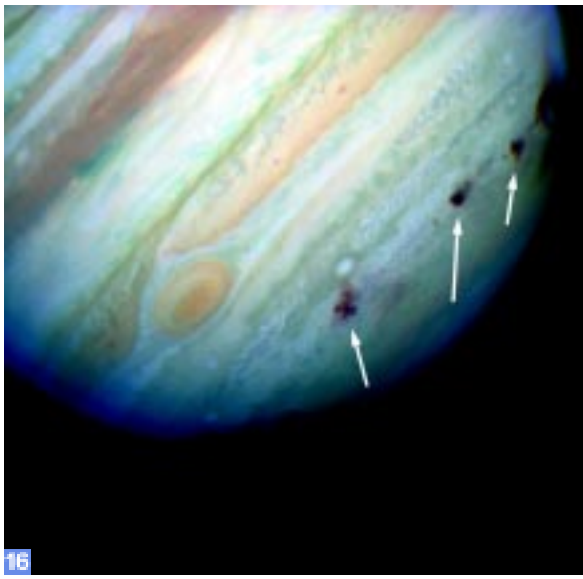
Dying stars shed material into interstellar space, sometimes gently and episodically, sometimes in explosive catastrophes. In either case, the ejected material is enriched in chemical elements produced in the interior, nuclear furnaces of these stars. This material "seeds" the interstellar gas and dust with the basic building blocks from which new stars, planets, and life may originate. Hubble's breathtaking images of dying stars provide a remarkably detailed understanding of the events preceding star death, how material is shed, and how that material interacts with the surrounding environment. The telescope also shows how the death process is influenced by each star's individual circumstances, such as a companion star, the presence of planets, a magnetic field, and rapid rotation. (Figures 12 & 13)

Perhaps the most spectacular example is Supernova 1987A, the nearest supernova seen in the last 400 years. An armada of telescopes has observed the supernova since its detection in February 1987. However, only Hubble has the resolution to trace, at sub-light-year scale, the evolving changes in both the fireball debris and the circumstellar ring of enriched gas. For the first time ever, Hubble observed the delicate ring structures left over from the pre-explosion evolution of the dying star. It also witnessed the blast debris from the supernova explosion expanding outward over time. Now, using Hubble, astronomers are seeing the innermost ring "light up" as the blast material collides with it.

Our Dynamic Solar System

Within our own solar system, the Hubble Space Telescope provides fascinating details about our neighboring planets. Hubble captured the first images of Pluto and its satellite Charon that were detailed enough to enable measurement of their masses and crude mapping of their surfaces. The telescope also showed that the atmospheres of the giant, gaseous outer planets, Uranus and Neptune, once thought to be bland and nearly featureless, actually possess very dynamic climates. Hubble treated scientists to stunning views of the northern and southern lights on Jupiter, Saturn, and Ganymede, as well as of the dynamic electrical interactions between Jupiter and its satellite Io. In 1995, Hubble afforded astronomers the rare opportunity to view Saturn's rings edge-on. The telescope's sharp resolution led to the discovery of an atmosphere surrounding the rings, the discovery of several new moons, and the observation of known moons in unexpected positions. The telescope has also monitored the weather on Mars and provided extraordinary images of seasonal changes at the Martian poles. (Figures 14 & 15)





In 1994, Hubble witnessed the collisions of the 21 fragments of Comet Shoemaker-Levy/9 with the upper atmosphere of Jupiter. These uniquely clear pictures revealed the enormous fireballs created when fragments entered the Jovian atmosphere at 140,000 mph and heated the atmospheric gases up to 50,000° F, cooking them into a stew of "soot" and organic molecules. Hubble tracked the movement of this "soot" over several weeks, allowing scientists to monitor the upper atmospheric winds. The telescope's observations of the impact sites provided new information about the composition and density of Jupiter's atmosphere. Hubble's Comet Shoemaker-Levy/9 campaign reminds humanity of our vulnerability and motivates us to remain vigilant of the space environment in which we exist. (Figure 16)

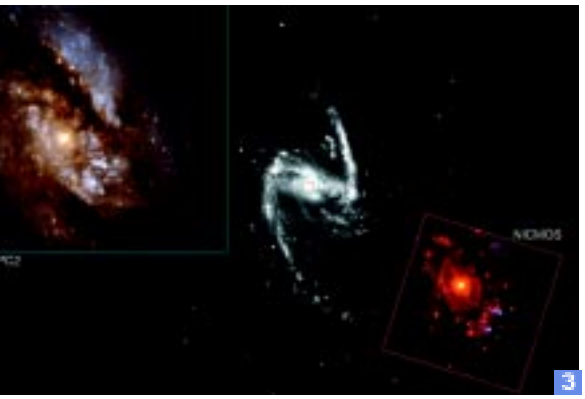
14. Saturn's aurora
15. Jupiter's aurora
16. Impact of Shoemaker-Levy/9 on Jupiter
17. Scientists awaiting the first images of the Shoemaker/Levy impact

IV. Hubble Continues to Expand Our Universe

As the Hubble Space Telescope enters its second decade, its discoveries continue to make front page news. The following are recent examples of how Hubble broadens our knowledge of the Universe in which we live.

Most Ancient Galaxies Ever Seen

With its infrared vision, Hubble has uncovered the oldest, faintest galaxies ever seen. Some may be over 12 billion light-years away, making them the farthest objects ever imaged in the Universe. (Figure 1)



A Cosmic Magnifying Glass

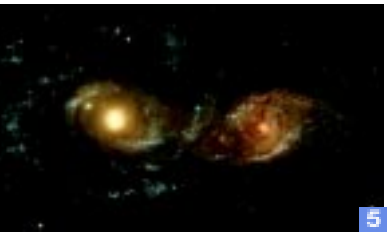
Hubble captures an image of a massive cluster of galaxies that act as a zoom lens in space. Called Abell 2218, this cluster's strong gravitational field magnifies the light of remote galaxies far behind it and works as a deep probe of the very distant Universe. (Figure 2)

Getting to the Heart of the Galaxy

A galaxy's central bulge holds secrets to how and when a galaxy is formed. Using Hubble's visible light and infrared cameras to penetrate deep into the cores of the galaxies, astronomers untangle the stars' true colors — a measure of age — from their apparent colors, which are made redder by interstellar dust. (Figure 3)

Lone Black Holes Work as Lenses

Hubble helps confirm the existence of isolated, stellar-mass black holes adrift in our galaxy. The telescope also shows how gravity from these black holes bends light like a powerful lens in space. (Figure 4)

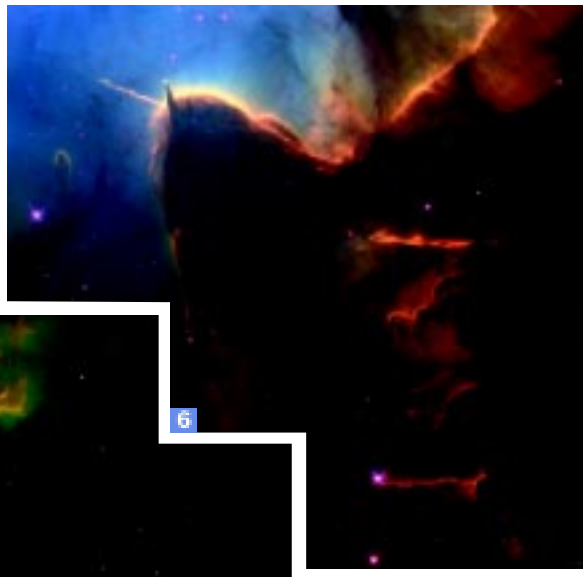


A Galactic Ballet

Hubble's high resolution captures the details of the strange and beautiful dance near the constellation Canis Major. Strong tidal forces from Galaxy NGC 2207 have distorted the shape of Galaxy IC 2163, flinging out stars and gas into long streamers that stretch out 100,000 light-years. Trapped in orbit around each other, these galaxies will eventually merge into a single, more massive galaxy. (Figure 5)

Doomed Stellar Nursery in the Trifid Nebula

Within the Trifid Nebula, Hubble reveals a stellar nursery being torn apart by radiation from a nearby, massive star. The embryonic stars are forming within an ill-fated cloud of dust and gas, which are destined to be eroded away by the glare of a massive neighbor. This stellar activity shows how the life cycles of stars like our Sun are intimately connected with their more powerful siblings. (Figure 6)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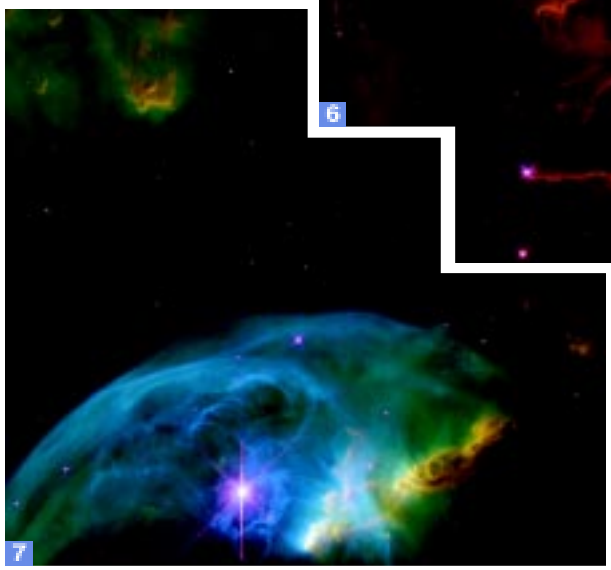
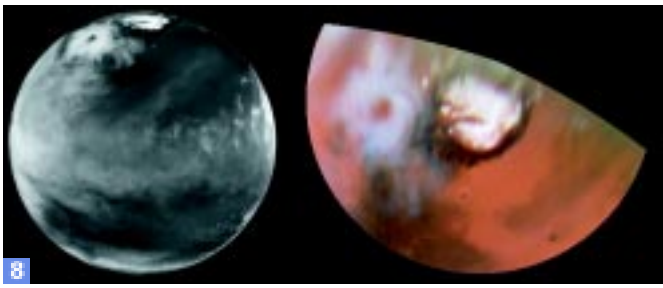
A Bubble in Space

Hubble reveals loops and arcs in the Bubble Nebula (NGC 7635) that have never been seen before. The origin of this curious bubble within a bubble may be due to a collision of two distinct stellar winds, but its origin is currently unknown. (Figure 7)


7

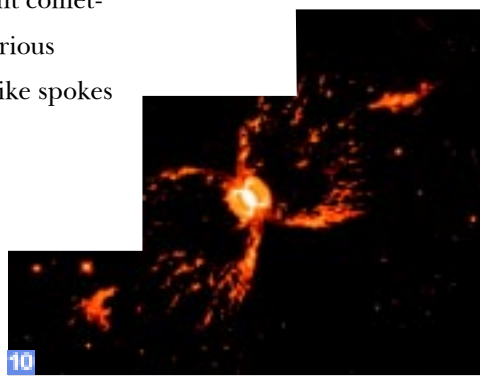
Giant Cyclone Near Martian North Pole

Using Hubble, astronomers have discovered an enormous cyclone raging in the northern, polar regions of Mars. Nearly four times the size of Texas, the storm is composed of water ice clouds like the storm systems on Earth, rather than of the dust typically found in Martian storms. (Figure 8)


8

The Eskimo Nebula

Hubble's sharp sight reveals that the "parka" of the Eskimo Nebula is really a disk of material with a ring of giant comet-like structures in the "fur." The tails of these mysterious objects all point away from the star's center, much like spokes on a wheel. (Figure 9)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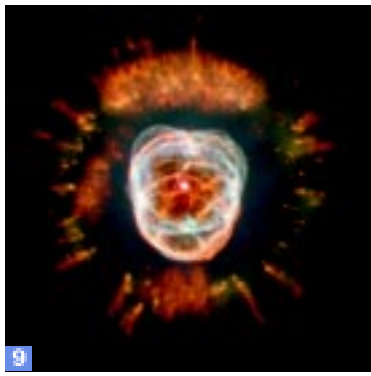

9

Star Pair Creates Unique Hourglass Shapes

Hubble reveals new details about the tempestuous relations between an unlikely pair of stars, a red giant and a white dwarf. Interactions between this pair may have sparked episodic outbursts creating an oddly shaped, gaseous nebula called the Southern Crab Nebula. Ground-based telescopes show a larger, hourglass-shaped nebula, but Hubble reveals another small, bright hourglass nestled in the center of the larger one, suggesting that separate outbursts occurred several thousand years apart. (Figure 10)

THE WHITE HOUSE

WASHINGTON

April 7, 2000

Warm greetings to everyone gathered at the NASA Goddard Space Flight Center to celebrate the 10th anniversary of the Hubble Space Telescope.

It was ten years ago this month that Dr. Steven Hawley eased the Hubble Space Telescope out of the space shuttle's cargo bay and gently placed it into orbit 380 miles above the surface of the Earth, thus beginning the remarkable tenure of the world's most famous telescope. The world anxiously awaited the first images from Hubble, and, while they were not as clear as we had hoped, these images were better than any previous telescope had ever produced. Four years later, following an extraordinary servicing mission that earned its management team the prestigious 1994 Collier Trophy, an improved Hubble Space Telescope continued the quest to unlock the secrets of our universe.

The HST has helped scientists see farther, clearer, and deeper into the past than we ever imagined. Over the past decade, HST images — some of which are now being immortalized as postage stamps — have been splashed across our newspapers and magazines. Textbooks have been rewritten as new images replaced old and as hypotheses have been converted into truths. HST images have aided scientists in the calibration of a cosmic measuring stick, the measurement of the expansion rate of our universe, the detection and measurement of black holes, and the exploration of the nature of quasars, the birth and death of stars, and the beginnings of new planetary systems.

These achievements alone have surpassed the expectations of the visionaries who developed the HST. And, owing to the foresight of NASA and its partners who designed the HST to be serviced on-orbit, newer and different instruments are fitted to Hubble on each servicing mission, enabling the HST to evolve as technology advances. As we celebrate this milestone, I salute the men and women responsible for designing, building, operating, and servicing the Hubble Space Telescope as well as the many scientists who continue to astound us with their discoveries. You have each played an important role in making the Hubble Space Telescope one of NASA's brightest stars.

Best wishes for a memorable anniversary celebration.

Bill Clinton

V. Hubble Captures the World's Attention

Over the past decade, the Hubble Space Telescope has captivated the world with its story of human resolve and exploration. Halfway through its 20-year mission, the telescope has become an international, cultural icon and part of the fabric of our lives. An entire generation of children has never known a world without Hubble.

Routine upgrades by Shuttle astronauts strengthen the unique bond between humans and Hubble. The relationship is dynamic and interactive: human interaction has enabled Hubble to evolve, providing cutting-edge discoveries for over a decade. Hubble's scientific productivity exceeds that of all other astronomical observatories, providing crucial training and insights for the next generation of innovators and explorers. It engages the ordinary citizen, with its ties running especially deep in industry and education.

President and Mrs. Clinton watching the launch of STS-95, October 1998.

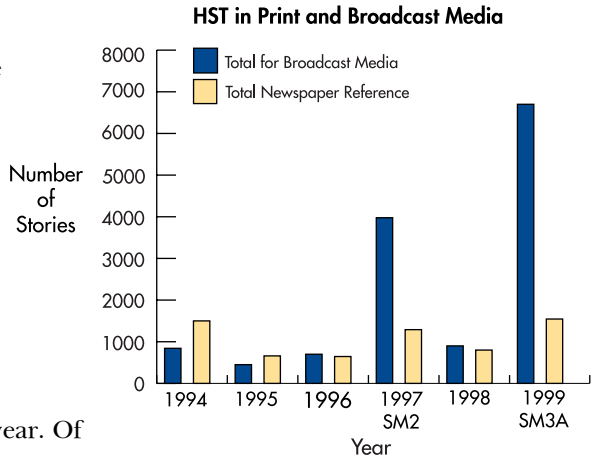
Hubble in the News

"Hubble's rate of discovery is simply unprecedented for any single observatory," says Dr. Ed Weiler, Associate Administrator for Space Science. "But what may be even more important in the long term is what Hubble has given to just about everyone on Earth. Hubble's spectacular images and discoveries of black holes, colliding galaxies, and bizarre objects at the edge of the Universe have been brought into millions of homes by newspapers, television, and the Internet."

From its spectacular launch and dramatic repair to its regular revelations about our Universe, Hubble is in the news more consistently than any other topic in space science. In addition to stories in the standard broadcast media, Hubble has maintained an ever-expanding presence on the World Wide Web.

Hubble in Print and Broadcast Media

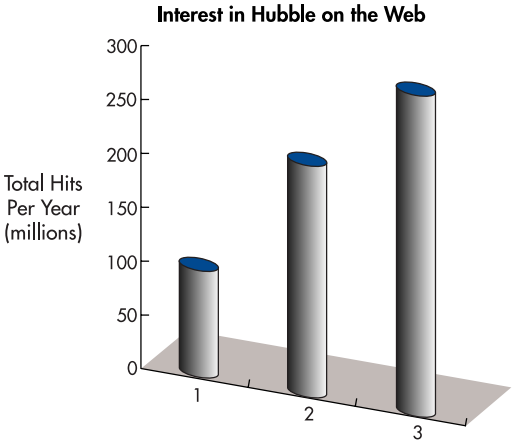
From the moment Congress made Hubble a reality, the public has been fascinated by the Telescope's progress, its seemingly insurmountable difficulties, and ultimately, its overwhelming success. In particular, the interaction of Hubble and its Space Shuttle servicing crews sparks the imagination of the public and the media.



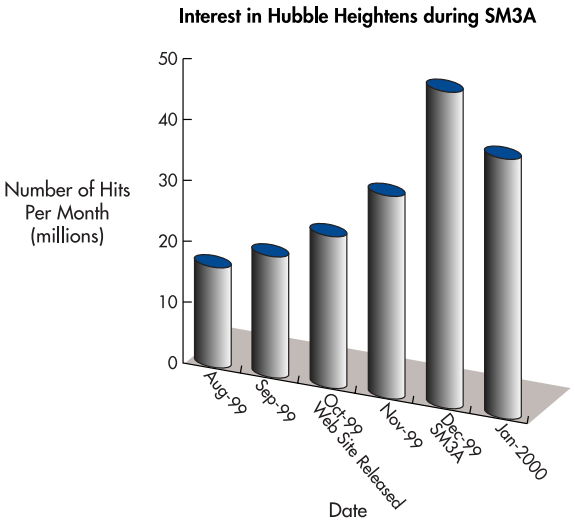
While many scientific satellites have captured the public's attention, none has rivaled Hubble in maintaining a consistent presence in the media and in popular imagination year after year. Of NASA's major science missions, the Hubble Space Telescope maintains the largest sustained presence in the news.

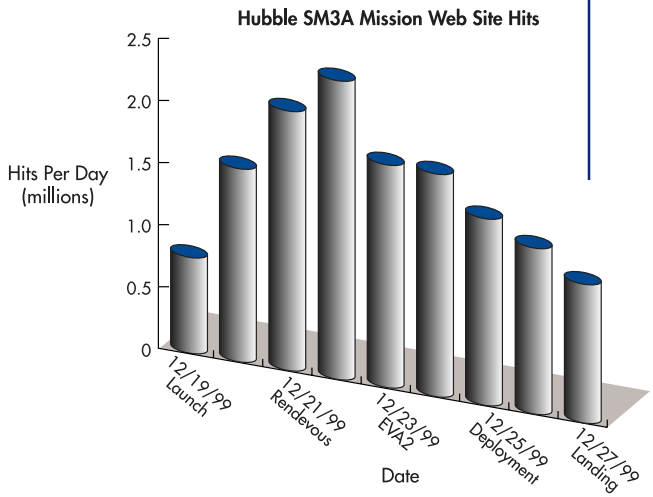
Hubble on the Web

The World Wide Web provides a unique way for people around the world to stay connected to the Hubble Space Telescope. Statistics from the official Hubble websites at the Space Telescope Science Institute and Goddard Space Flight Center (GSFC) show an ever-increasing interest in Hubble images, science, and related news. These sites averaged 18 million hits per month during the non-servicing time periods in 1999.



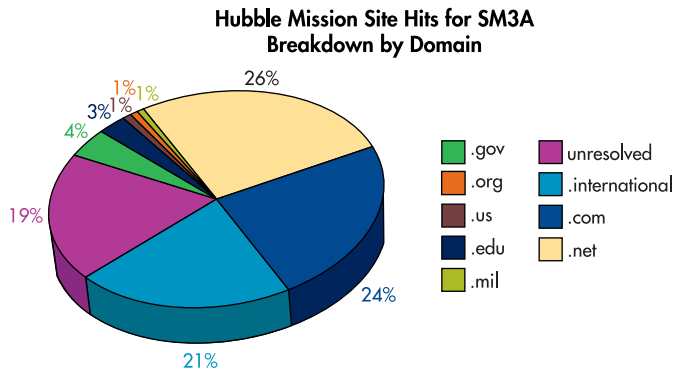
Servicing heightens interest in Hubble. Web site statistics graphically show the increased level of public interest during the SM3A servicing mission. Visits to the public Hubble Mission web site peaked at over 2 million hits per day during spacewalks, with the combined Hubble sites averaging six times more visitors than in non-servicing mission periods.





The Human Connection

Interest in Hubble comes from around the globe. Visitors to the Hubble mission web site are a diverse representation of age, occupation, and geographic location. The audience breakdown shows that interest in Hubble is not limited to members of government or the scientific community, but includes access from businesses, educational institutions, and international addresses, as well as individuals across the United States, as shown in the chart below.



Excerpts from the Hubble SM3A Mission Web Site Guestbook Show Overwhelming Support for NASA and the Hubble Program

- "Thank you for bringing space travel to us. Watching the liftoff of Discovery on NASA TV tonight was amazing. I am a teacher and I am currently involved in the Mars Millennium Project with my students. Watching the liftoff still leaves me in wonder. I can remember watching when man made his first steps on the moon. I look forward to the day when we take our first steps on Mars. Thank you to Congress for the continued funding to the space program. Thank you for bringing the adventure and education to us. Our prayers are with you."

- "Nothing lasts forever without repair. Robots can't do this work. Have successful and safe mission."

The STS-103 Crew on their way to the launch pad

- "Greetings from Holland. Please forward the following message towards the crew: Have a safe blast off, a very successful mission AND last but not least a very successful return to the base. Looking forward to see the progress on this site."

- "Thanks for the experience of being a part of the launch, it's great for the mind. Also, Thank you, Congress for the funding."

- "Excellent work. The universe is ours, thanks to all your hard work guys."

- "...know how important this instrument is to us, though we may be bricklayer, accountant, or teacher. It is our sharp eye on the universe, our window on creation, and our time machine. Thank you NASA ... CONGRATULATIONS!"

- "Greetings, this just boggles the mind as to what is out there. And all we can do is look, but without you doing what you do best, we couldn't even do that. This Earth is such a small place, why can't people learn to get along with one another."

VI. Hubble Partners: Taking the Initiative

Industrial and educational partners from across the nation and around the globe play critical roles on Hubble's science and engineering teams. In addition to performing scientific observations and analysis, these partners team with NASA on hardware design, fabrication, and integration and testing, as well as spacecraft operations and information technology. This partnership of scientific expertise and technological excellence allows the Hubble Space Telescope to continue as one of the "crown jewels" of NASA year after year, mission after mission.

Hubble Team Meeting

Hubble and Industry - Partners in Innovation

No enterprise as complex as Hubble can be successful without the dedication and support from a wide range of technical disciplines. These are provided through Hubble's industry partners, bringing the most advanced and cost-effective solutions to the unique challenges of creating, operating, and strengthening humankind's most powerful observatory. This combined Hubble team routinely makes the personal sacrifices necessary to keep our observatory operating flawlessly.

Industry Partners

AASC
ACI Electronics Corporation
Advanced Circuit Technologies
Alatec Products
Alliant Techsystems, Inc.
AlliedSignal
Almag Plating
AMP Inc.
Apnet
Arrow Zeus Electronics
Associated Spring
Astrium GMBH
Astrium Ltd.
Astro Instrument Corporation
Atlantic Science and Technology
AURA
Aviation Equipment
Avnet Inc.
BAE Systems
Ball
Bally Ribbon Mills
Barden Precision
Barr Associates, Inc.
BD Systems
Bechdon
BEI Sensors and Systems Company
Boeing
Bradley Enterprises
Brush Wellman
C-S Metals
CalTech
Cannan
Capstone Electronics
Castrol Inc.
CDA InterCorp
Ceramic to Metal Seals
CES
Clement Engineering
Climax Specialty Metals
Coastal Optical Systems
Conexant
Contravis Space
Copper & Brass Sales
Courtaulds Performance Films
CSA Engineering, Inc.
CSC
CYTEC-FIBERITE
Denton Vacuum, Inc.
Eagle Precision
Eastern Plating
EER
Energy Solutions International, LLC
Epner Technology
E.V. Roberts
Fastener Depot
Fry Steel
General Dynamics
Genesis Engineering Co., LLC
Global Science & Technology
Hardware Specialty Co.
Helicoflex Co.
Hernandez
HISCO

Honeywell Technical Solutions
Hypertronics Corporation
Indium Corp of America
Industrial Retaining Ring
Interface Welding
ISI
Jackson & Tull
Jodin Yvon-Spex
Kaydon Custom Bearings
K R ANDERSON
Kenig Aerospace
Kyocera America, Inc.
Lake Shore Cryotronics
Litchfield Precision
Lockheed Martin
Lockwood Software
LSEI
M & D Machine
ManTech
Marconi Applied Technologies
Marlow Industries
Maryland QC
Max Levy & Associates
Maxwell Technologies
McMaster Carr
Mega
Melles Griot
Minco Products, Inc.
Nanonics Corporation
Newark Electronics
Newport Corporation
Nusil Technology
Oceaneering Space Systems
OerliKon Contravis AG
Omitron
Omnetics
Optical Filter Corporation
Optical Research Associates
Orbital Science Corporation
Pacific Coast Technology
Penn Camera
Photo Chemical
PNE
PRO-PAC
Raytheon
Research Devices, Inc.
Research Electro Optics
Robert C. Byrd Institute
Rockwell Science Center
SAES Getters
SAFT America, Inc.
Samson Metals
SAVA Industries
Sea Wire & Cable
SGT
Sheldahl Co.
Sherburn Electric Corporation
Southwest Products Company
Spacecraft System Engineering Services
Space Systems Integration
Specialty Manufacturing
Spectrum Laser
Stern and Stern
SUMATECH
Surmet
SVG Tinsley Laboratories
Swales Aerospace
Tifco-Spline
Titanium Industries
Tomas & Betts
TOPER Manufacturing
Toshiba America
Total Plastics
TFE
TTI, Inc.
TW METALS
Tyco Engineered Systems
Unisys
United Supertek, Inc.
University of Arizona
University of California
USA
Vantage Systems
Washington Valve
Wolcott Park
Yellow Springs Instruments
Zeus West

Hubble and Education - Investing in Our Future

The scientific enterprise of Hubble draws upon an international group of universities and research organizations. The students at these institutions learn critical research methods using the data from Hubble. They convert it from raw numbers into our civilization's most accurate and detailed view of the physical Universe. Public outreach activities convey the excitement of Hubble's discoveries to an entire generation of school children. These future leaders and explorers will have the benefit of a view of the Universe that was speculation and conjecture just a decade ago.

Hubble and Innovative Science Education

Each year, over 7000 school groups visit the Hubble Integration Facility. Among them is the SUNBEAMS program (Students United with NASA Becoming Enthusiastic about Math and Science). The program is designed to encourage positive and enthusiastic attitudes towards math and science among middle school students. Hubble is so well known to students through their schools and through the media that it is uniquely suited to illustrating the connection between real-life skills and the abstract concepts of science. Students visiting the Hubble testing and integration facilities can interact with Hubble staff and handle materials in the Thermal Systems Support Lab, where Hubble's protective blankets are sewn. This unique, hands-on opportunity engages students directly, creating an immediate connection between Hubble's breathtaking images and the people and skills necessary to make the telescope work. Hubble's very real human connection opens children's minds to a world of possibilities for the future. (Figure 1)

Hubble Engineering Competition

An engineering competition, sponsored by the Hubble Program, the GSFC Education Office, the GSFC Public Affairs Office (PAO), and the GSFC PAO Contractors Consortium, was held with the regional participation of middle school students. The competition involved integrated disciplines such as engineering, science, and mathematics. This outreach event focused on school teams learning and utilizing the engineering process to solve the real-life or potential real-life issues encountered by engineers working with Hubble. (Figure 2)

1. Presentations at the Hubble Engineering Competition
2. SUNBEAMS students touring Hubble facilities

The competition was a valuable education initiative encouraging the development of higher-level thinking skills and problem-solving skills. The use of the engineering process at the middle school level enhanced students' ability to practice critical thinking in a team environment. At the same time, it provided a background for career choices in engineering. This type of competition is more challenging than the typical science fair because contestants must use their scientific knowledge to devise a creative solution within a relatively short period of time.

The NASA Strategic Plan mandates that we involve the education community in our endeavors to inspire America's students, create learning opportunities, enlighten inquisitive minds, and communicate widely the content, relevancy, and excitement of NASA's missions and discoveries. Educational programs such as Hubble's help ensure that a continuing pool of scientists, engineers, and technologists will be ready to meet the needs of the 21st century.

The Hubble Team Goes to School

As part of the Hubble tenth anniversary commemoration, Hubble personnel created a presentation program and visited schools across the Washington, DC metro area and in Virginia, Maryland, Connecticut, and California. These school visits were designed to inspire students to excel in math and science by communicating Hubble's accomplishments over the past decade. In the Washington D.C. area alone, between mid-April and late-May of 1999, nearly 19,000 students in 300 schools were reached.

Educational Outreach at the Space Telescope Science Institute

At the Space Telescope Science Institute (STScI), where Hubble's images are processed and analyzed, education plays a major role in outreach. STScI supports teachers of grades K-12 by providing web-based and printed materials that promote science, math, and technology skills. The award-winning *Amazing Space* web site provides interactive lessons and activities, which are based on national educational standards. *Amazing Space* modules are developed by teams of scientists, teachers, graphic artists, web programmers, curriculum specialists, and education evaluators. STScI also provides posters, trading cards, lithographs, bookmarks, and information specifically designed for teachers and students without access to the Web.

PCs in Space is used nationwide

In addition, STScI supports science museums and planetaria. It provides Hubble expertise, multimedia shows, and exhibit materials tailored to the needs of each venue. STScI partnered with Goddard and the Smithsonian to develop an extensive, traveling Hubble exhibit, which debuted at Chicago's Adler Planetarium in June 2000. Over the next five years, a large and small version of this exhibit will travel to museums and planetaria across the country. These exhibits, along with STScI's other educational outreach products, bring the fun of math and science to our children through the awesome power of Hubble's images.

PCs in Space Educational Software

NASA teams with industry partners and educators to create interactive, educational software showcasing Hubble images to inspire students around the world. *PCs in Space*, Jackson and Tull's free software, is an innovative program available through the Internet. The educational material incorporates Hubble's latest discoveries into existing curricula, enhancing the overall educational experience. This enormously successful program has reached 4.5 million students in the past five years, sparking enthusiasm for space science among a new generation.

Partners in Higher Education

In 1999, these institutions were awarded merit-based research grants to analyze Hubble data:

Arizona State University
Australian National University
Boston University
Bowling Green State University
California Institute of Technology
Canadian Military College
Carnegie Institute of Washington
Carnegie Mellon University
Case Western Reserve University
Catholic University of America
Centre d'Etudes de Saclay (CEA Saclay)
Clarkson University
Columbia University
Copenhagen University Observatory
Cornell University
Crimean Astrophysical Observatory
Dartmouth College
Dublin Institute For Advanced Studies
Ecole Normale Superiure de Lyon
Georgia State University Research Foundation
Harvard University
Harvard-Smithsonian Center for Astrophysics
Haverford College
Herzberg Institute of Astrophysics
Imperial College of Science Technology and Medicine
Indiana State University South Bend
Indiana University System
Institute For Advanced Study
International School for Advanced Studies
Konkoly Observatory
Kyiv University
Leiden Observatory
Liverpool John Moores University
Louisiana State University
Lowell Observatory
Lund University
Macalester College
Massachusetts Institute of Technology
McMaster University
Michigan State University
Middlebury College
New Mexico State University
Northern Arizona University
Northwestern University
Observatoire de Geneve
Observatoire de Grenoble
Observatoire de Marseille
Observatoire de Paris
Observatoire Midi-Pyrenees
Observatorio Astronomico Nacional
Ohio State University
Oxford College of Emory University
Paul Scherrer Institute
Princeton University
Queen's University
Rice University
Royal Greenwich Observatory
Royal Observatory Edinburgh
Ruhr-Universitat Bochum
Rutgers the State University of New Jersey
San Francisco State University
Skidmore College
Smith College
South Carolina State University
Southwest Research Institute
St. Mary's University
State University of New York at Stony Brook
Sternwarte der Universitaet Bonn
Sterrewacht Leiden

Stockholm University
Technion-Israel Institute of Technology
Tel Aviv University
The Academy of Art & Science
The Johns Hopkins University
The Pennsylvania State University
The Queen's University of Belfast
The University of Virginia
Towson State University
Universidad Autonomia de Madrid
Universidad de Chile
Universidad de Concepcion
Universidad Nacional Autonoma de Mexico
Universidade de Sao Paulo
Universidade Federal de Santa Catarina
Universidade Federal do Rio Grande do Sul
Universita degli Studi di Bologna
Universita degli Studi di Catania
Universita degli Studi di Milano
Universita di Firenze
Universita di Pisa
Universitaet Erlangen-Nurenberg
Universitaet Potsdam
Universitat Basel
Universitat Bonn, Astronomische Institute, Sternwarte
Universitat Hamburg, Hamburger Sternwarte
Universitat Heidelberg
Universitats-Sternwarte Gottingen
Universitats-Sternwarte Munchen
Universite de Liege
Universite Laval
Universite Paris XI
Universiteit van Amsterdam
Universities Space Research Association
University College London
University of Alabama
University of Arizona
University of Bristol
University of British Columbia
University of Calgary
University of California - Berkeley
University of California - Davis
University of California - Los Angeles
University of California - San Diego
University of California - Santa Barbara
University of California - Santa Cruz
University of Cambridge
University of Central Lancashire
University of Chicago
University of Cincinnati Main Campus
University of Colorado at Boulder
University of Delaware
University of Denver
University of Durham
University of Edinburgh, Institute of Astronomy
University of Florida
University of Guam
University of Hawaii
University of Hertfordshire
University of Illinois at Urbana - Champaign
University of Keele
University of Kentucky
University of Leicester
University of Manchester
University of Maryland
University of Massachusetts
University of Melbourne
University of Michigan
University of Minnesota - Twin Cities
University of Montreal
University of Nevada - Las Vegas
University of New South Wales
University of North Carolina at Charlotte
University of North Carolina at Raleigh
University of Nottingham
University of Oklahoma Norman Campus
University of Oregon
University of Oslo
University of Oxford
University of Padova
University of Pennsylvania
University of Pittsburgh
University of Rhode Island
University of Sheffield
University of Southern California
University of St. Andrews
University of Sussex
University of Sydney
University of Texas at Austin
University of Texas at El Paso
University of Toledo
University of Toronto
University of Utrecht
University of Victoria
University of Virginia
University of Wales, College of Cardiff
University of Washington
University of Waterloo
University of West Virginia
University of Wisconsin - Madison
University of Wyoming
Valparaiso University
Villanova University
Wellesley College
Wesleyan University
Western Kentucky University
Western Michigan University
Whitman College
Yale University
York University

VII. Hubble and NASA's Strategic Goals

The NASA Strategic Plan is a major step toward shaping the Space Science Program of the 21st century. Guided by this plan, the space science community can continue to change the way we think about our place in the Universe.

Hubble's unique and original design meets the challenges set forth by NASA. Hubble is also an integral part of NASA's Origins Program, which is designed to aid us in obtaining knowledge of our cosmic roots. Throughout its first decade, Hubble has maintained a standard of excellence in exploring the development of space and human enterprise, researching and developing advanced technologies, and advancing and communicating scientific knowledge.

Hubble and its continuing servicing missions are central to the implementation of the science goals for NASA and the Origins Program:

- Hubble has provided information crucial to understanding the structure of our Universe.
- Hubble continually tests physical theories and reveals new phenomena throughout the Universe, especially through the investigation of extreme environments.
- Hubble helps scientists understand how both dark and luminous matter determine the geometry and fate of the Universe.
- Hubble instruments have helped us understand the dynamic and chemical evolution of galaxies and stars and the exchange of matter and energy among stars and the interstellar medium.
- Hubble has expanded our knowledge of how stars and planetary systems form together.
- Hubble has provided detailed images that assist us in understanding the nature and history of our solar system, and what makes Earth similar to and different from its planetary neighbors.

We can utilize the knowledge provided by HST, including the development of cutting-edge technologies to advance our knowledge and to improve the quality of life on Earth.

"I am honored to be the leader of an organization that has this Hubble team."

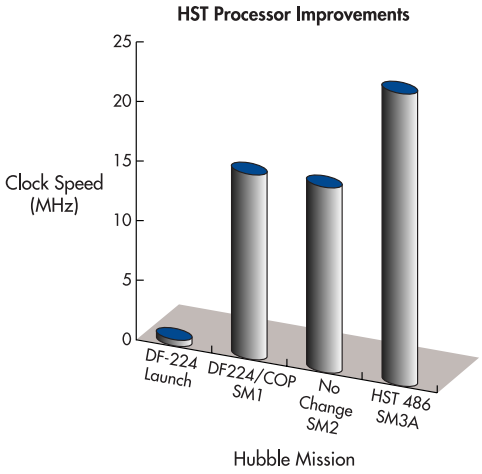
— Daniel S. Goldin, NASA Administrator

VIII. Hubble and Advanced Technologies

From detector technology to astronaut tools, the Hubble Program is continually seeking to optimize performance. The 10-year-old telescope is essentially a new machine. Upgrades, maintenance, and creative innovations maximize Hubble's scientific return and ultimately benefit many aspects of our everyday life. From manufacturing to medicine, these numerous technological advances enhance the U.S. economy and our standard of living, making Hubble a valuable investment for our future.

Computer Processing Improvements

During Servicing Mission 3A, astronauts replaced Hubble's original main computer, a DF-224/coprocessor combination, with a completely new computer based on the Intel 80486 microchip. The new computer is 20 times faster and has six times as much memory as the one it replaced. In a good example of NASA's goal of "faster, cheaper, better," commercially developed, commonly available equipment was used to build a new computer at a fraction of the price it would have cost to build a computer designed specifically for the spaceflight environment.



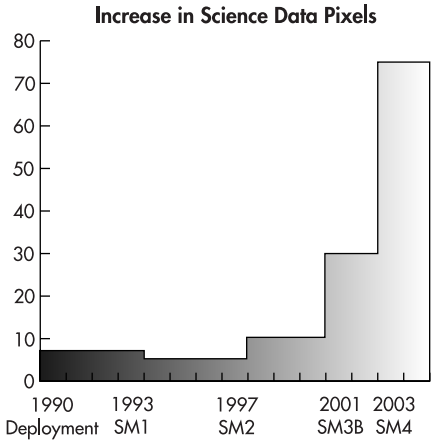
The greater capabilities of the new computer are increasing Hubble's productivity. The computer software also uses a modern programming language, which decreases software maintenance cost.

Data Storage Capability

With the addition of a second Solid State Recorder (SSR) on SM3A, Hubble's data storage capability dramatically increased. The science data archiving rate is now more than ten times greater than 1993 rates.

Prior to SM2, Hubble used three mechanical reel-to-reel tape recorders designed in the 1970s. In February 1997, astronauts replaced one of these recorders with a digital SSR. In 1999, SM3A astronauts removed a second mechanical recorder and installed another digital SSR.

Unlike the reel-to-reel recorders they replace, the SSRs have no reels, no tape, and no moving parts that can wear out and limit lifetime. Data is stored digitally in computer-like memory chips until

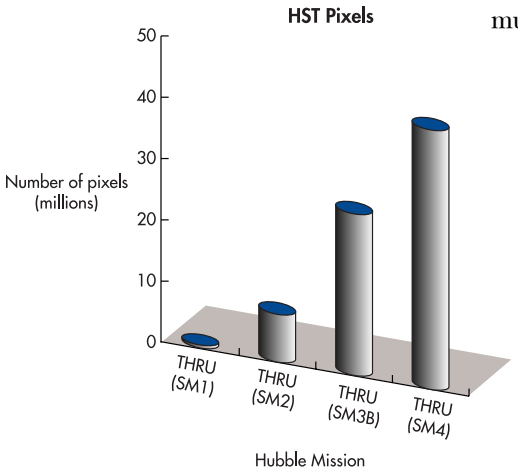


Hubble's operators command its playback. Although an SSR is about the same size and shape as the reel-to-reel recorder, it can store ten times as much data: 12 gigabits of data instead of only 1.2 gigabits. This greater storage capacity allows the second generation of Hubble's advanced-technology scientific instruments to be fully productive.

Detector Technology

Hubble's state-of-the-art detector technology allows the telescope to capture and process faint amounts of light from the far reaches of space.

Charge-coupled device (CCD) detectors are commonly referred to as the "film" of digital cameras, but that description hardly does justice to this incredibly useful technology. Modern CCD detectors match the resolution of film, but they surpass film in several key performance areas. For example, they are capable of operating over a much wider wavelength range. A single CCD detector can record data from the infrared to the x-ray energy band, making this technology extremely adaptable. Their sensitivity to light is far superior to film over these large wavelength ranges.

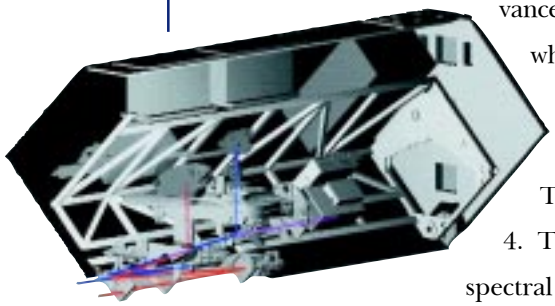


In addition, images can be read out of a CCD in seconds, much faster than film can be developed. Most importantly, CCDs record images digitally, allowing the information to be stored and manipulated by a computer. These versatile qualities have lead to the rapid transfer of CCD technology into industrial, medical, and consumer applications. The CCD is now the "detector of choice" in products ranging from automotive quality control monitors to breast biopsy systems to video cameras.

The accelerated progress in CCD development over the past two decades is due in large measure to the efforts of the HST Program, which has continuously driven the leading edge of this technology. Hubble scientists realized early on that broad wavelength sensitivity, coupled with the ease of digital data analysis, makes CCD detectors ideal for astronomy. CCDs were aboard the Hubble Space Telescope when it launched in 1990. Successive generations of science instruments pioneered CCD technology enhancements. These efforts have led to the production of larger format, more sensitive, and more reliable detectors, enabling Hubble to deliver exceptional scientific data.

Advanced Camera for Surveys (ACS)

The Advanced Camera for Surveys, to be launched on Servicing Mission 3B, employs a 16-million pixel focal plane (consisting of two state-of-the-art, 8-million pixel CCDs) with advanced, performance-enhancing coatings. These coatings allow the detectors to absorb up to 85 percent of the photons that strike them. The combination of the instrument's large field of view and superior sensitivity will improve Hubble's scientific capabilities by a factor of ten. The Advanced Camera CCD program also targets specific process enhancements, which reduce image artifacts and improve manufacturing yield.

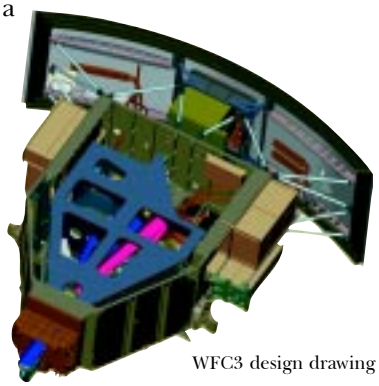


ACS design drawing

Wide Field Camera 3 (WFC3)

The Wide Field Camera 3 is planned for launch on Servicing Mission 4. This dual-channel instrument will provide an unprecedented, wide-spectral range view of the Universe. Its two-detector system spans the near-ultraviolet to the near-infrared. The Hubble program is focusing its efforts on developing a CCD with high sensitivity over both the visible and ultraviolet spectrum. This would provide a new capability in the near-ultraviolet for both astronomical and earthbound uses. Building upon the advances made by ACS, these detectors would provide higher sensitivity and lower noise than ever achieved in detectors of this size. For the long wavelength (infrared) channel, the technological advance is comprised of an IR detector system that is cooled exclusively by a thermal electric cooler to -120° C (150 Kelvin). This reduces cost and complexity when compared with the traditional methods, which use cryogens or other cryogenic cooling systems. WFC3 will improve Hubble's scientific capabilities by a factor of twelve.

The science community is eagerly anticipating the discoveries that will be made with these new highly efficient instruments. In the meantime, Hubble's CCD efforts are already paying off on Earth. Each new development broadens the applications for, and improves the performance of, these detectors.



WFC3 design drawing

Cosmic Origins Spectrograph (COS)

In 2003, astronauts will begin a new era in ultraviolet spectroscopy when they install the Cosmic Origins Spectrograph (COS) instrument into Hubble. One of its major goals is to measure the distribution of matter in the almost empty space between galaxies. This is a major puzzle as we complete our census of where all the matter in the Universe resides. Most of this matter is in the form of hydrogen. Measurements in the ultraviolet are key since this gas has unique signatures in this wavelength region. This innovative instrument uses a simple and elegant optical design, coupled with advanced ultraviolet detectors. It improves sensitiv-

ity levels by a factor of ten compared with previous instruments. Using this new capability, Hubble scientists hope to better understand the characteristics of the matter between and within stars and galaxies.

Cryogenic Cooler

Astronauts installed the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) on Hubble in 1997. Its infrared (IR) vision allowed scientists to probe dark, dusty, never-before-seen regions of space. Solid nitrogen ice kept NICMOS cool and allowed it to conduct infrared science. In 1999, with its supply of ice exhausted, NICMOS became dormant. On SM3B, astronauts will retrofit NICMOS with a new cooling system that will return it to active duty. The heart of this system is the NICMOS Cryogenic Cooler (NCC).

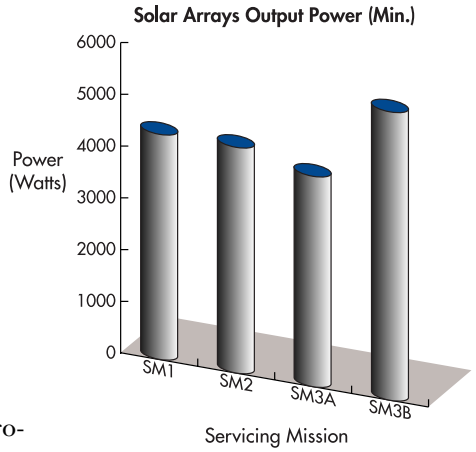
The NCC is a state-of-the-art, mechanical cryocooler that will potentially increase NICMOS's life span from 1.8 years to more than 5 years. It uses rapidly rotating microturbines, the fastest of which spins at over 400,000 rpm (over 100 times the maximum speed of a typical car engine). It will cool the infrared detectors to -200° C, or 70 Kelvin. The NCC operates with virtually no mechanical vibration. Such vibration would cause Hubble to shake and affect image quality, much as a shaky camera affects picture quality.

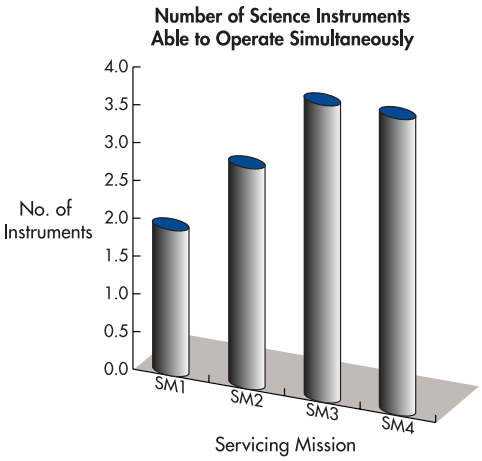
The Hubble Project successfully demonstrated this new technology aboard STS-95 in 1998. This was the first on-orbit test of a high-performance, high-efficiency, mechanical cryocooler. The test took place less than 20 months after cryocooler development began—an extremely short time for bringing a new technology into the space applications portfolio.

The cost to develop and install the NCC is approximately $19 million, while the cost of NICMOS was $120 million. Installing a new cryocooler will triple the lifetime of the instrument, ensuring a greater scientific return on the original investment. This revolutionary technology paves the way for exciting advances in IR astronomy on both Hubble and the Next Generation Space Telescope.

Solar Arrays Increase Simultaneous Science Capabilities

The addition of new, rigid solar arrays on SM3B will provide Hubble with increased electrical power-generating capability. This will enhance science productivity by allowing up to four science instruments to operate simultaneously. Advancements in solar cell technology make it possible for these new arrays to produce 20 percent more power, even though they are 30 percent smaller than the current set, which was installed on Hubble during SM1.





The smaller size decreases on-orbit drag and slows Hubble's rate of orbital decay. These smaller, stiffer arrays also are easier for the astronauts to work around during servicing missions.

The panel supports on the arrays are made of lithium-aluminum, which is stronger, lighter, and tougher than the type of aluminum commonly used in spacecraft construction. These supports are much less sensitive to the extreme temperature changes of Hubble's orbit. (Within each 97-minute orbit, the temperature outside Hubble spans about 149° C (300° F).

The Hubble Program bought solar panels from the production line of a commercial system of communications satellites. Purchasing off-the-shelf panels saved considerable time and expense.

The HST Lubricant Applicator

The Lubricant Applicator in use.

During the first and second servicing missions, the astronauts discovered that several bolts keeping the large Aft Shroud doors closed were exhibiting high running torques during operation. In an effort to solve this problem, the Hubble team developed a tool to apply a thin film of lubricant to the threads of the door bolts. While a simple task here on Earth, applying a viscous fluid in the vacuum of space had never been performed before. Care had to be taken to avoid getting the grease on the astronaut's gloves or the rest of the highly sensitive spacecraft. In response to this challenge, the innovative Hubble team developed the HST Lubricant Applicator. With this new tool, the astronauts were able to apply a small amount of grease on the threads at each location without contaminating themselves or the spacecraft. Although the tip of the tool was designed specifically for applying grease to the Hubble's door bolts, it can easily be modified to fit almost any feature of any other space structure.

Lithium Ion Battery

A prototype Lithium Ion (Li-Ion) battery pack for NASA's Power Ratchet Tool (PRT) was flown during Servicing Mission 3A. The PRT, a power tool developed by GSFC, is used to service Hubble. This was the LiIon battery's first test in space.

NASA teamed with the Air Force Research Labs, Wright-Patterson AFB, and SAFT America Inc., to develop and certify this new, cutting-edge battery technology for human space flight. The Li-Ion battery chemistry as compared to nickel cadmium (NiCad) provides superior energy density, over 50% higher voltage, excellent charge retention, and high cycle life. This ten-cell battery pack could fit in a small, portable, 12-volt commercial power drill, yet supplies over 40 volts. While 24-volt power drills are currently available, their battery packs are bulky, making them hard to hold for long periods of time and difficult to operate when working in tight spaces. The Li-Ion battery will reduce overall logistics and maintenance costs for NASA, compared to the current technology because each one will be used on multiple missions.

NASA contimues to develop this technology for use in its next generation power tool. Our goal is to get the same power in a smaller, more compact battery.

Diamond-Hard Carbon Coating

A revolutionary, diamond-hard coating will cover tiny parts on the NICMOS cryogenic cooler. Called UltraC Diamond™, this film-like coating is tough, slippery, and approximately 1/100th the thickness of a human hair. This is its first space use on titanium and the first time any hard, carbon coating will be used on such small, complex, and precise machinery.

During normal operation, the cryocooler's tiny circulator shaft will spin at 90,000 rpm. To minimize friction and wear, the shaft and bearings need a very thin, hard, slippery coating. The Hubble team looked at various other coatings, but only UltraC Diamond™ met their rigorous requirements. The coating is a prime example of the economic value-added benefits of Hubble technology. It was developed by Surmet Corporation, and the Hubble Program funded the extensive testing required to qualify it for flight.

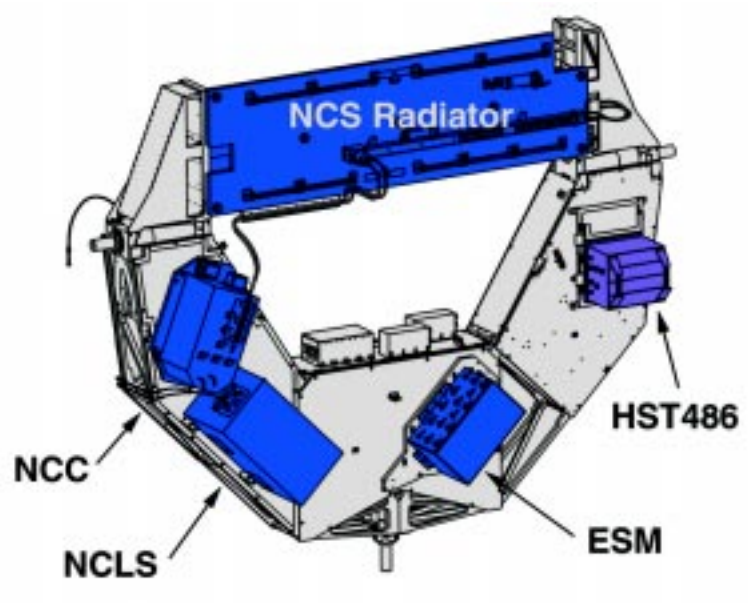
Experts foresee widespread applications and enormous benefits for NASA and private industry. This tough and nearly frictionless coating is ideal for applications such as semiconductor manufacturing, high-speed micromachines, miniaturized satellites, and prosthetics. It is also well suited for use in power plant turbines, air conditioners, and automobile engines.

Hubble and the Shuttle Program – A Test Bed in Space Adds Scientific Value

In October 1998, the Hubble Team conducted the HST Orbital Systems Test (HOST) on board STS-95 ("The John Glenn Mission"). HOST provided an on-orbit test bed for key pieces of new Hubble hardware, including a new, main computer (HST486), NICMOS Cryogenic Cooler (NCC), and digital data recorder. By flying in an orbit similar to Hubble's, HOST helped engineers determine how the new equipment would perform on Hubble.

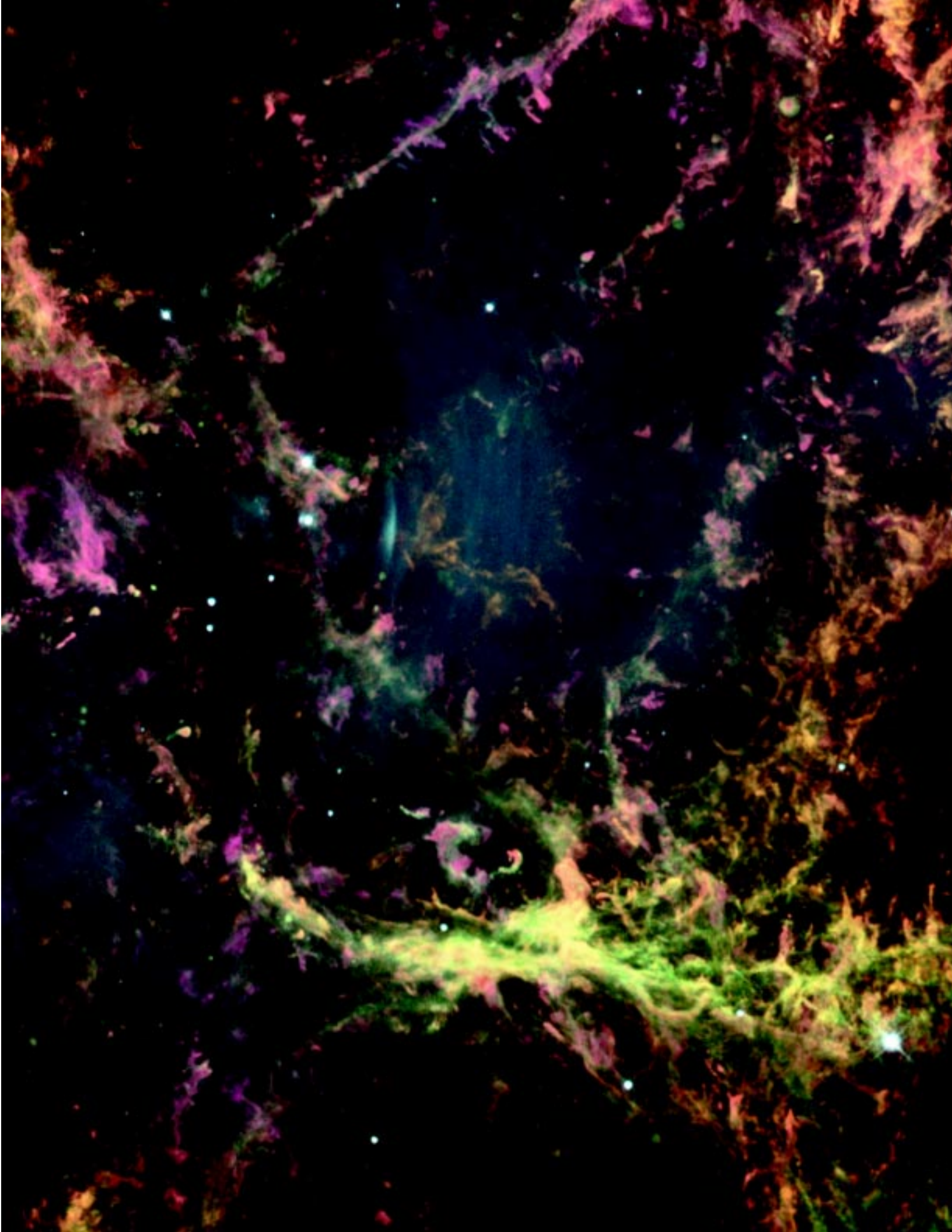
HOST engineers monitored the effects of radiation on Hubble's new hardware. All the new technologies aboard HOST performed optimally. In 1999, astronauts installed the new computer and data recorder on Hubble. The cryogenic equipment will become part of the telescope in 2001.

The success of the HOST mission underscores the value of the Shuttle and humans in space. It also illustrates the Hubble Program's philosophy of using new and advanced technology to maximize science return.



HST Orbital Systems Test Platform

The NICMOS Crogenic Cooler (NCC), NICMOS Cooling Loop Simulator (NCLS), Electronic Support Module (ESM) and NCS Radiator worked together to test the operation of the revolutionary NICMOS Cooling System (NCS).



IX. Vision 2000: The New Hubble Control Center System (CCS)

Imagine something remarkably new and remarkably powerful, right at one's own fingertips. It's the Hubble Control Center System (CCS) and it opens the window to the world of Hubble Space Telescope operations. Imagine using an ordinary personal computer to view the inner workings of Hubble, and monitor its actions as operations are run. This is the new CCS. It is how spacecraft engineers and flight operations personnel now fly the telescope from "Hubble Mission Control" at the Goddard Space Flight Center.

CCS software is the central hub for controlling the telescope's day-to-day operations and supporting servicing mission upgrades and repairs. The radical re-engineering of the CCS flight and ground systems, which began in 1996, demonstrates the Hubble Program's commitment to using the latest technology to improve efficiency and cut costs. The redesigned CCS has dramatically improved overall Hubble performance and drastically reduced the cost of operations and systems maintenance. Compared against the original goal for Vision 2000, the new CCS era is proving to be a huge success. The ongoing operations and maintenance costs have more than eclipsed the 60 percent savings benchmark. The CCS has successfully supported routine spacecraft operations since February 1999, including the flawless servicing mission in December 1999.

Spacecraft subsystem engineers use CCS to control and monitor HST operations during SM3A in the Space Telescope Operations Control Center at Goddard

By establishing an integrated Product Development Team (PDT), in which civil servants and contractors were melded into a single, badgeless team, the Hubble Program was able to successfully complete this massive restructuring under an extremely tight schedule. This integrated team delivered eight major releases in approximately three years, demonstrating the benefits that come from a highly motivated, co-located team.

The CCS redesign went well beyond replacing outdated software and hardware. It streamlined flow, eliminated redundant systems, and provided a user-friendly interface for the operators and spacecraft engineers. With CCS, engineers are no longer tied to their workstations. They can access CCS functions from anywhere in the world with a standard, off-the-shelf computer and an Internet or modem connection.

The CCS Graphical User Interface (GUI) software developed for Hubble is so user friendly and successful that it was commercialized and is now being used by Lockheed Martin on the Globalstar telecommunications program.

Architecture

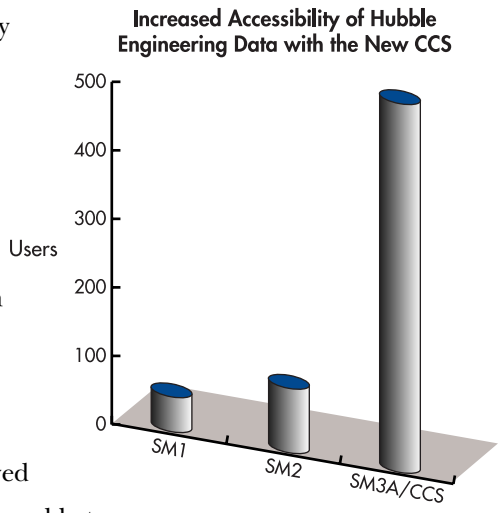
The improved CCS greatly reduced architectural complexity and will reduce future maintenance costs. It consolidated the functions of the five original systems into a single, streamlined system that provides the full spectrum of spacecraft control, analysis, data management, command management, and subsystem calibration. Its highly scalable client-server architecture supports single computers as well as multi-processor strings. This is especially useful for servicing where CCS is tailored to different sizes to meet varied requirements. These range from single-computer, flight hardware ground testing systems to the large scale real-time servicing mission operational system.

Security

CCS design and development have been security-conscious from the start. The current design is based on concentric networks, which are linked by up-to-date security features. This design provides controlled transmission of data among the networks while absolutely protecting the telescope and its operating systems, command functions, and databases from unauthorized use or change.

Efficiency and Flexibility

The Hubble Program decided in early 1995 that the then-emerging, web-related technologies would become a key architectural component in creating an efficient data delivery system. CCS is now capable of delivering engineering data directly to the user, regardless of geographic location. This stands in sharp contrast to the former practice of requiring that the user be located at the data source. CCS allows quicker response to spacecraft anomalies, decreased travel expenses, and improved team interaction. It also enables easier and quicker setup of the remote NASA control centers at Johnson Space Center and Kennedy Space Center, which play vital roles in Hubble's servicing missions.



Information Access

A wealth of spacecraft information now available to Hubble personnel proved invaluable during SM3A. Users can define data requests in real time and are able to monitor conditions that have changed on the spacecraft. The previous system, used during SM1 and SM2, only allowed users to access limited real-time spacecraft telemetry information from a handful of custom workstations located at a few facilities.

AUTOMATION

The process for collecting and merging real-time and spacecraft-recorded data has been fully automated in CCS. The engineering data is kept online for 30 days, then rolled off to a large, robotic tape archive and a data warehouse archive. This process and the source of the data are transparent to the user. Eventually, CCS data archives will hold all of Hubble's engineering data since deployment.

SPEED

CCS now enables users to make very rapid, complex queries over wide time spans. The new data warehouse technology stores the data using schemes that combine complex query capabilities with excellent performance. For a systems engineer using the self-service features of CCS, the average response time for data delivery was cut by a factor of six.

MONITORING

CCS has been designed to monitor itself at the network, hardware, and software application levels, further reducing maintenance and operations costs.

The Hubble Program has achieved its goals of improving user productivity, and reducing maintenance and operations costs with this new system. CCS provides a secure, highly distributed command and control system that will ensure the success of Hubble's operations throughout its second decade.

PRODUCTIVITY INCREASES

CCS reduces:

- staff for spacecraft operations by 50%
- science planning by 10%
- data processing by 40%

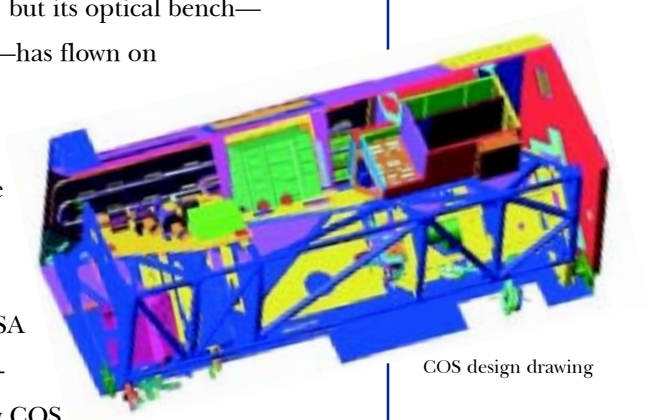
Task	Before CCS	After CCS	Improvement
Observing Hours per Year	2400	4815	2X
Target of Opportunity Lead Time	2 wks.	24 hrs.	14X
Time from Proposal to Data Receipt	19 wks.	7 wks.	3X
Reference Database Change	14 wks.	1 hr. - 2 wks.	7X
Average Response Time	6 hrs.	1 hr.	6X

X. Hubble And Space Assets: Servicing Adds Economic Value Through Reuse

Hubble's modular design allows for on-orbit instrument upgrades during planned servicing calls. The ability to refurbish the returned science instruments has proven to be a cost-effective way to enhance the telescope with the latest technology. By installing the new technology in recycled modules, NASA avoids "reinventing the wheel" and reduces the overall cost of science data. Future Hubble instruments will have 10 to 20 times more capability at half the cost of previous instruments.

Cosmic Origins Spectrograph (COS): Optical Bench Reuse

In 2003, astronauts will fit Hubble with a new ultraviolet instrument, but its optical bench—the frame that holds the instrument's powerful optics and detectors—has flown on Hubble before.



COS design drawing

The Cosmic Origins Spectrograph (COS) reuses the bench from one of Hubble's original instruments, the Goddard High Resolution Spectrograph (GHRS). This instrument successfully fulfilled its mission and was returned by Space Shuttle astronauts in 1997. NASA and the Hubble industry team conducted rigorous testing and determined that the 20-year-old optical bench could be reused in the new COS instrument. Ultrasonic and x-ray inspections showed that the bench was still structurally sound. In fact, it was in virtually the same condition as when it was delivered to NASA in 1981. By reusing the GHRS bench, the Hubble Program saved $1.3 million and hundreds of work hours. This is the first-ever refurbishing of a Hubble science instrument.

COS will allow scientists to observe faint, ultraviolet targets both inside and outside of distant galaxies. It will help astronomers understand the interstellar medium, the formation and evolution of galaxies, and the origins of stellar and planetary systems. COS will provide Hubble with ultraviolet spectroscopic capability from 2003 to the end of its 20-year mission.

Wide Field Camera 3 (WFC3)

WFC3 is a fourth-generation instrument for Hubble. It is designed to replace the Wide-Field Planetary Camera 2 (WFPC2), which was installed in Hubble during SM1 in 1993. WFC3 will have greater throughput and sensitivity than WFPC2. The WFC3 project is designed to take advantage of much of the hardware, software, and experience from the previous instruments.

By virtue of Hubble servicing, WF/PC1 was returned on Servicing Mission 1. As a result, approximately 30 percent of its assemblies can be re-flown on the WFC3 instrument. This significantly lowers the cost of WFC3. A prime example of the savings generated by this approach is the Selectable Optical Filter Assembly (SOFA). This previously flown, highly complex mechanism, with its 48 filter slots, will be refurbished and tested prior to flight. Thus, the costly design and development cycle is eliminated. In addition, the mission risk associated with flying a new mechanism design for the first time is mitigated.

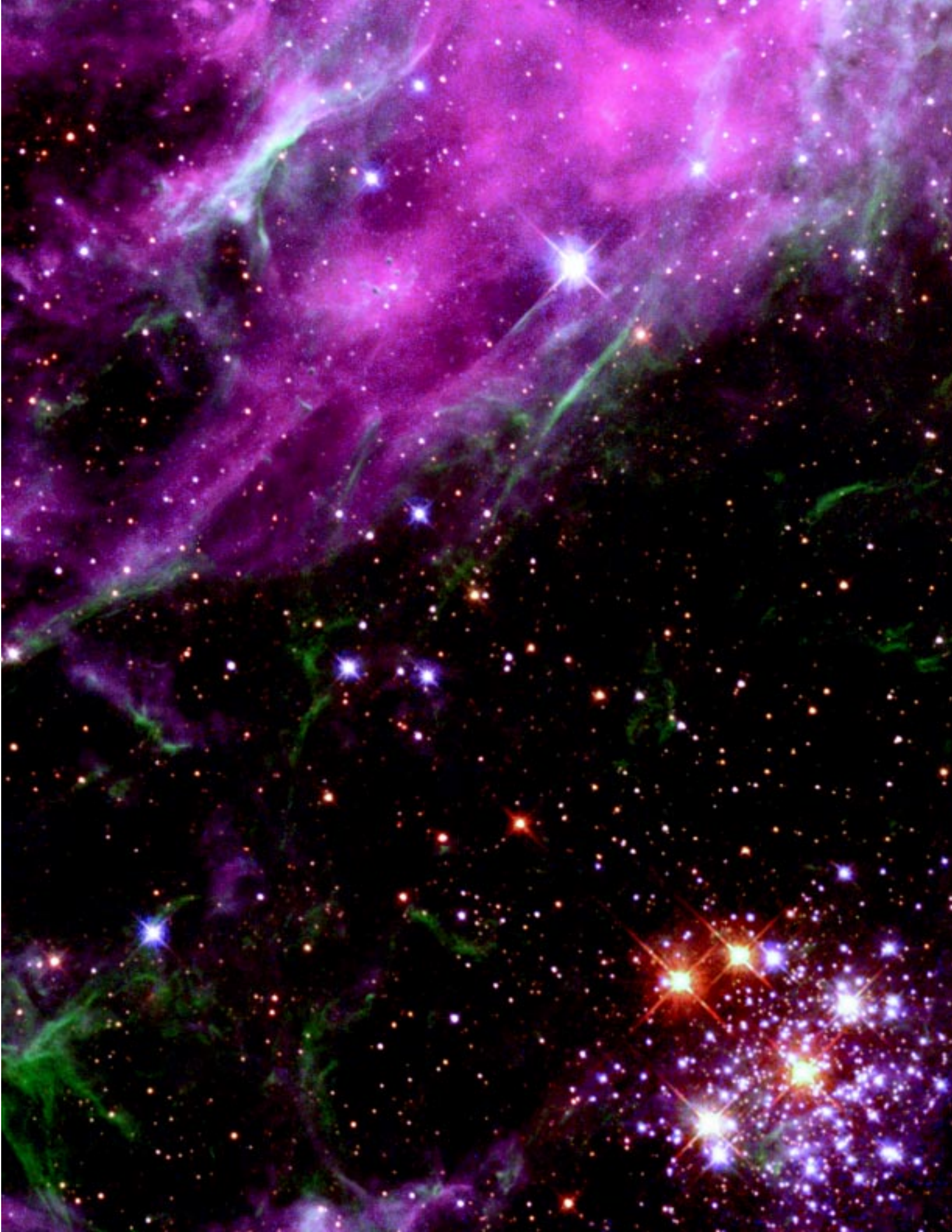
Wide-Field Planetary Camera being removed on-orbit during the first Servicing Mission.

The filters for WFC3 will consist of the most popular filters from WF/PC1, WFPC2, and ACS. In addition, as new detector technologies become available, these are being incorporated into the instrument design to maximize the instrument's scientific productivity. The NASA, industry, and university teams who worked to successfully build WF/PC1 and WFPC2 are working together again to bring us WFC3, leveraging their expertise and experience to provide a superior instrument at modest cost.

Refurbishing Fine Guidance Sensors (FGSs)

During SM3A in 1999, astronauts replaced one of the three fine guidance sensors (FGSs), which are part of Hubble's pointing control system. Hubble's FGSs are undergoing a systematic program of refurbishment and upgrading. In "round-robin" fashion, one FGS per servicing mission is being replaced, returned to the ground, disassembled, and refurbished. It is then taken back to Hubble on the next servicing mission to become the replacement unit for the next FGS to be serviced. By the conclusion of SM4, all three FGSs will have been brought up to optimum condition.

This refurbishment process is the most effective use of these space assets and the best way to save valuable resources. Each refurbishment of a previously flown FGS costs $10 million. If purchased new, each would cost NASA—and ultimately the American taxpayers—$70 million apiece. If NASA purchased new FGSs instead of refurbishing existing units, three replacement FGSs would cost $210 million. By renewing existing hardware, the cost for three FGSs drops to $30 million—which represents $180 million in cost savings.



XI. 2000 and Beyond

World class teamwork
World class technology
World class science

Hubble's return on investment for tangible and intangible benefits should please Hubble's main investors, the American public. The design of the Hubble Space Telescope has proven that human intervention in space is a resounding success, keeping Hubble operating at peak performance throughout this decade. Hubble continues to be the most productive, cost-effective satellite mission ever launched. Hubble's visionary, modular design allows the telescope to be fitted with new instruments and components at substantial cost savings. The dedication of all members of the Hubble Program from NASA, ESA, industry, and the scientific community remains as strong as when Hubble was launched a decade ago.

Hubble's place in history as a pathfinder for new scientific discoveries is guaranteed. The telescope's future looks bright as well. Continued servicing of Hubble's systems ensure the telescope's optimal performance. The installation of new instruments, including the Advanced Camera for Surveys, Cosmic Origins Spectrograph, and Wide Field Camera 3, offer limitless possibilities of unexpected insights into our Universe throughout the next decade.

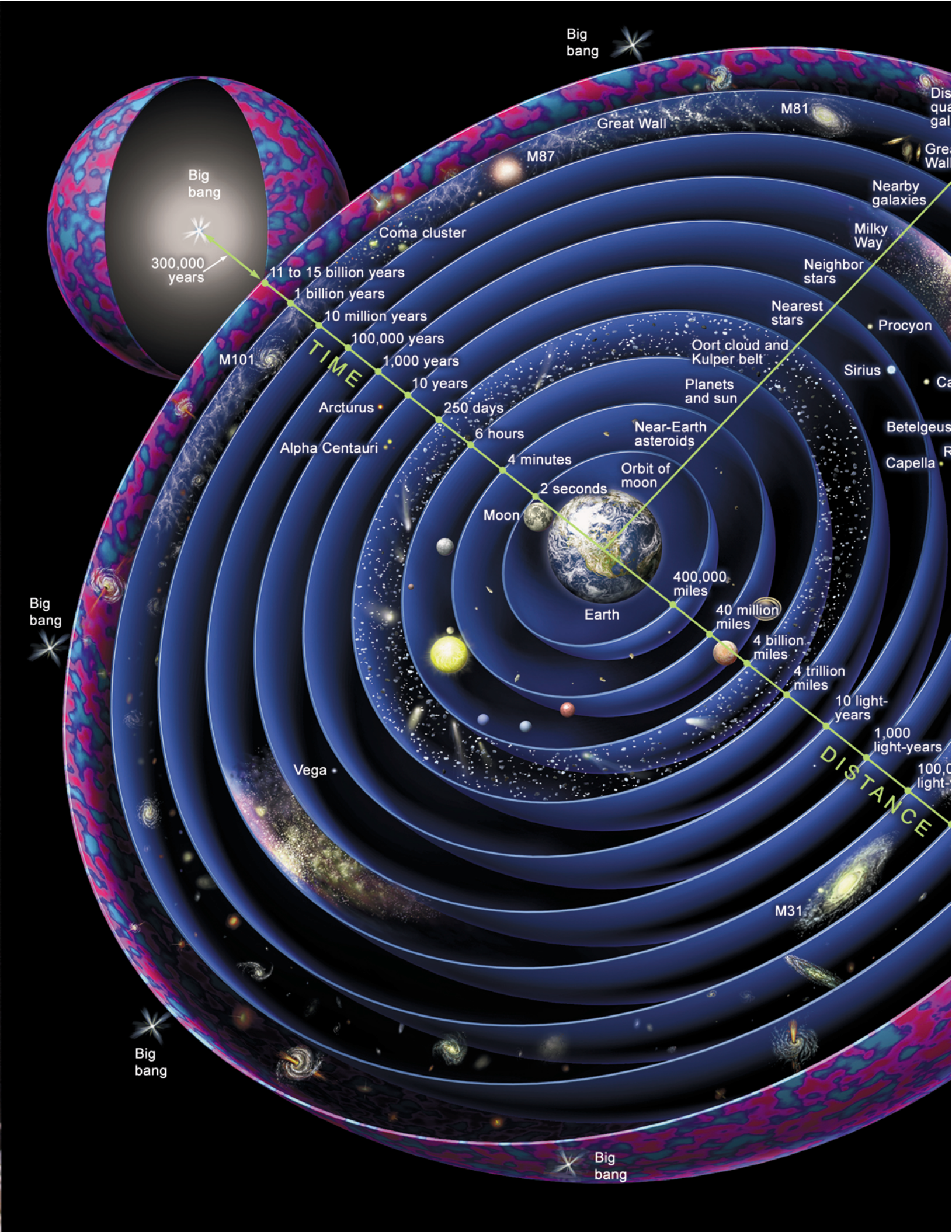
We have begun to scratch the surface of the mystery that is our Universe, and through Hubble's innovations and technical advances we have made significant strides. However, the age-old questions of mankind still remain:

How did the Universe begin?
What is it made up of?
What is our place in it?
How does it all work?
Is there anyone else out there?

Astronaut Steve Smith giving a "thumbs up" during STS-103.

It is the possibility of shedding light on these fundamental questions that launched the Hubble Program and that continue to motivate the Hubble team and capture the imagination of the world.

The human desire for exploration has found a special partner in the Hubble Space Telescope. We have now had one decade to get to know each other, and we can look forward to at least one more. Each time we send a mission into space to enhance Hubble's abilities, we are proclaiming our desire to take another step closer to answering these universal questions. This unique human connection allows each of us here on Earth to feel the magic of discovery for ourselves.


Big bang
Big bang
300,000 years
11 to 15 billion years
1 billion years
10 million years
100,000 years
1,000 years
10 years
250 days
6 hours
4 minutes
2 seconds
TIME
Big bang
Big bang
Big bang
Big bang
M101
Arcturus
Alpha Centauri
Vega
Coma cluster
M87
Great Wall
M81
Nearby galaxies
Milky Way
Neighbor stars
Nearest stars
Procyon
Sirius
Oort cloud and Kulper belt
Planets and sun
Near-Earth asteroids
Orbit of moon
Moon
Earth
400,000 miles
40 million miles
4 billion miles
4 trillion miles
10 light-years
1,000 light-years
DISTANCE
M31
Betelgeus
Capella

NP-2000-8-077-GSFC

"I think there is no better proof than these pictures that NASA's capability to send humans into space to work on Hubble has had a vital role in space science and the renaissance in astronomy we're now seeing,"

- Dr. Ed Weiler
NASA Associate Administrator for Space Science.