Hubble Space Telescope

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Abstract

The Hubble Space Telescope (HST) is widely viewed as one of the most important scientific and technological achievements of modern times, comparable in its impact to Galileo's first use of the telescope for fundamental astronomical research in 1610. Although it is not the first astronomical observatory to exploit the benefits of viewing the Universe from outside Earth's atmosphere, it is the first to realize fully the gain in *clarity* of astronomical images that results from the absence of atmospheric turbulence. Without having to contend with the atmosphere's rapidly fluctuating refraction and transmission, the HST's angular resolution is limited primarily by light diffraction at the entrance aperture of its 2.4-meter telescope.

Earth's atmosphere glows from the emission of light by excited atoms and molecules. It is opaque at ultraviolet wavelengths below about 300 nm and strongly absorbs in broad intervals of the near-infrared band above 1100 nm. Outside the atmosphere, the optics of the Hubble telescope and its scientific instruments provide sharply focused and remarkably stable images against a very dark sky at wavelengths that span approximately 4.5 octaves—110 to 2500 nm. The ability to concentrate light from a point or compact source into a tightly focused image superposed on a dark, low-noise background allows the relatively small-aperture HST to detect extremely faint astronomical objects in its direct imaging mode—fainter by as much as 1.5 stellar magnitudes (four times fainter) than current 8–10 meter mountaintop telescopes.

This unique combination of capabilities has made HST one of the most productive scientific tools of modern times—and one of the most sought after. Observing time on Hubble is allocated by a process of competitive peer review on the basis of scientific research proposals submitted yearly by astronomers from all over the world. The demand for using HST exceeds the available time typically by a factor of 6:1. The result is an almost continuous stream of amazing scientific accomplishments; many were unanticipated before Hubble's launch. These include the deepest view of the Universe ever acquired that revealed protogalaxies whose light was emitted when the Universe was less than 10% of its present age, the first demographic census of supermassive black holes at the centers of galaxies, accurate calibration of the age and expansion rate of the Universe, strong evidence acquired in partnership with ground-based observatories that cosmic expansion is accelerating, and frequent observation of dusty disks containing complex structures of rings and gaps possibly indicative of planet formation around other stars.

The HST is essentially unique among robotic space missions because it was designed for a long lifetime in space, enabled by regular orbital visits by crews aboard the Space Shuttle who implement technological upgrades of Hubble's instruments and other systems and perform a variety of maintenance and repair tasks on the spacecraft. This concept of preplanned, periodic servicing missions by Shuttle astronauts allowed the correction of a serious optical flaw in Hubble's telescope that was discovered shortly after it was first deployed in 1990. The first HST servicing mission in 1993 demonstrated that humans can carry out arduous and complex work during a period of many days, encumbered by bulky spacesuits in the severe environment of low Earth orbit. Without the intervention of the Human Space Flight Program, the unmanned Hubble observatory would undoubtedly have come to be viewed by history as an embarrassing failure. Instead, Hubble became a national icon.

1. Introduction

The Hubble Space Telescope (HST) is widely viewed as one of the most important scientific and technological achievements of modern times, comparable in its impact to Galileo's first use of the telescope for fundamental astronomical research in 1610. Although it is not the first astronomical observatory to exploit the benefits of viewing the Universe from outside Earth's atmosphere (Figure 1), it is the first to realize fully the gain in *clarity* of astronomical images that results from the absence of atmospheric turbulence. Without having to contend with the atmosphere's rapidly fluctuating refraction and transmission, the HST's angular resolution is limited primarily by light diffraction at the entrance aperture of its 2.4-meter telescope.

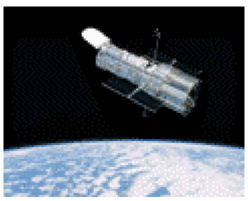

Figure 1. The Hubble Space Telescope, newly refurbished after Servicing Mission 3B in March 2002, orbits approximately 550 km above the surface of Earth.

[Full View]

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2. Hubble's History

The achievements of the Hubble Space Telescope are built on a legacy of scientific and technological progress that spans nearly a century (1). Its development and successful mission is the work of thousands of people. However, two individuals, Edwin P. Hubble (1889–1953) and Lyman Spitzer (1913–1997), stand out as seminal figures in the history that led to the HST. In the 1920s and 1930s, the observatory's namesake, Edwin P. Hubble (2), and his colleagues provided the first compelling observational evidence of two important properties of our Universe: the Universe is populated by a large number of widely separated individual galaxies of which our own Milky Way galaxy is but one; and the universe is systematically expanding, growing larger with time. These two discoveries set humankind on course toward our present understanding, as of the beginning of the twenty-first century, of the origin, composition, evolution, and fate of the universe and everything within it. These are the themes that dominate scientific research with the Hubble Space Telescope, and naming it in honor of Edwin Hubble is particularly apt.

Lyman Spitzer is universally recognized as the “father” of the Hubble Space Telescope. Although others had recognized the potential advantages of astronomical telescopes above the atmosphere, as early as the 1920s, Spitzer's classified study in 1946 for the RAND project (later to become the RAND Corporation) first articulated the scientific rationale that ultimately provided the underpinnings for modern space astronomy. Spitzer's greatest contribution, however, was that he championed the dream of a large telescope in space within the astronomical community, to the public, and to the federal government and relentlessly pursued that dream for the rest of his life (3). During the period 1965–1977, Spitzer and his collaborators, in particular astronomers John Bahcall and George Field, built the necessary scientific and political consensus that led the U.S. Congress in 1977 (fiscal year 1978) to initially authorize and fund the detailed design and development of what was then called “The Space Telescope (ST).”

In early design studies the ST had been conceived as a 3-meter telescope, commonly referred to as the Large Space Telescope (LST). In 1975, NASA reduced the proposed aperture to 2.4 meters to limit the program's expected costs. The reduced size of the telescope simplified its manufacture and testing, allowed the telescope and its surrounding spacecraft to fit within the envelope of the Space Shuttle's payload bay, and made it easier to achieve accurate and stable pointing of the orbiting telescope toward astronomical targets. The 2.4-meter aperture was judged sufficient to provide the light gathering capability and angular resolution necessary for the ST's most important scientific objectives, including detection of “standard candle” Cepheid variable stars in the galaxies of the Virgo cluster, an essential step to providing a major improvement in our knowledge of the distance scale, rate of expansion, and age of the Universe (4).

The project's support in Congress rested in part on the understanding that tangible support would also come from outside the United States. Consequently, the Space Telescope was born as a collaboration between NASA and the European Space Agency (ESA). The agreement between the two agencies required ESA to provide the solar arrays from which the Space Telescope obtains its electrical power, a scientific instrument for the observatory (the faint object camera), and a portion of the staff required to operate the observatory after it was launched. In return, ESA was guaranteed a minimum of 15% of the observing time on the telescope for use by European astronomers.

NASA instituted a rather complex organizational structure, drawn from government, industry, and the academic world, to build and operate the Space Telescope. The Marshall Space Flight Center in Huntsville, Alabama, was designated as “lead center” for the development and launch phases of the mission and also was directly responsible for developing the optical telescope and the spacecraft. NASA selected the Lockheed Missiles and Space Company of Sunnyvale, California, to build the spacecraft and to integrate all of the flight hardware under contract to Marshall. The Perkin-Elmer Corporation of Danbury, Connecticut, was selected to design and fabricate the extremely precise telescope optics, fine guidance sensors and supporting structure, also under a Marshall contract. NASA assigned to the Goddard Space Flight Center in Greenbelt, Maryland, the responsibility for managing the development of the scientific instruments and the operational systems that would be used to command and control the Space Telescope from the ground. After launch and initial checkout of the integrated telescope, spacecraft, and scientific instruments, “lead center” responsibility for the long-term operations and servicing of the observatory was transferred to Goddard.

To design and develop the collection of sensitive instruments that would be the basic tools for astronomical research with the Space Telescope, in 1977, NASA selected five teams drawn from universities, industry, and government laboratories, as well as an interdisciplinary Science Working Group, to guide the overall project. After considerable deliberation, NASA concurred with the formally expressed desires of the astronomical community that the scientific program of the observatory be managed by an “independent” entity external to the government (5). Thus, in 1981, NASA signed a contract with the Association of Universities for Research in Astronomy (AURA) to create the Space Telescope Science Institute in Baltimore, Maryland.

The tumultuous early years of design and development work on the Space Telescope has been thoroughly (and grippingly) described by R.W. Smith (6). At the outset, the project was seriously underfunded and understaffed, and the technological problems to be surmounted were formidable. Although optical telescope technology applicable to the ST had reached an advanced state of development for national security applications, other required technologies were less mature circa 1980. Serious and costly problems were encountered, for example, in designing and fabricating the complex, lightweight, composite (graphite epoxy) structure on which the primary and secondary mirrors were mounted. Another challenging design problem centered on the extraordinary pointing stability (±0.007 seconds of arc rms) required for the telescope's line of sight for extended periods of time, to preserve the extremely high angular resolution provided by its tightly focused images (approximately 0.05 seconds of arc at visible wavelengths). When the ST program started in 1977, NASA anticipated an approximately 6-year development period, culminating in a launch on the Space Shuttle in the last quarter of 1983. This schedule proved far too aggressive, given the limitations of funding, the technical challenges, and the unwieldy management structure responsible for the observatory's development. Eventually the untenable nature of these problems was recognized. In 1983, NASA undertook a major reorganization of the ST program and provided a critical infusion of additional funding. At that time, the observatory was renamed Hubble Space Telescope (HST).

As the 1980s unfolded, the design, fabrication, and testing of all of the systems from which a complete HST observatory was to be assembled, never ceased to be severely challenging. Continuing technical problems, budget pressures, and schedule erosion compounded each other. One contributing factor described at the time was that the HST was developed as a "protoflight" unit. No budget existed for a "prototype" of the observatory to identify and resolve problems inherent in the design. Instead, these problems were first manifested in the actual flight hardware and that hardware frequently had to be redesigned and rebuilt as such problems arose. Nevertheless, the manufacture of the HST progressed. Testing of the scientific instruments was completed at the Goddard Space Flight Center in March 1984, and they were subsequently transported to Lockheed Missiles and Space Company (LMSC) in Sunnyvale, California. On 29 October 1984, the Optical Telescope Assembly (OTA) began its cross-country journey from the Perkin-Elmer facility in Danbury, Connecticut, to LMSC. It arrived at Moffett Field, California, on a "Super-Guppy" aircraft on 1 November. On 15 February 1985, the meticulous process of assembling the telescope, the spacecraft, and the scientific instruments into an integrated flight system was completed. The remainder of 1985 was devoted to an intensive and demanding test program of the assembled observatory.

NASA selected 21 June 1986 as the target date for delivering the completed HST to the Kennedy Space Center to begin preparations for its launch on Space Shuttle Atlantis on the following 18 August. On 6 January 1986, NASA announced a delay in the projected launch date of the HST to 27 October 1986. Three weeks later, on 28 January 1986, Space Shuttle Challenger and its crew were tragically lost, and the entire Shuttle fleet was grounded indefinitely. When it might be possible to begin the Hubble mission could no longer be foreseen and was no longer the primary concern of anyone associated with America's space program.

After years of anticipation and delay, expectations among astronomers, government officials, the press, and the public were unrestrained as Shuttle Discovery (STS-31) lifted off from Launch Pad 39B at the Kennedy Space Center at 8:33:51 A.M. on 24 April 1990, carrying the crown jewel of astronomy, the Hubble Space Telescope in its payload bay. On the following day, astronaut/astronomer Steve Hawley gently maneuvered the Shuttle's robotic arm (RMS) to lift the 12-ton observatory out of its moorings and raise it to a position high above Discovery. While the HST was still in the grasp of the RMS, ground controllers at the Goddard Space Flight Center deployed the spacecraft's high-gain antennae and solar arrays and moved the arrays to the correct orientation to capture solar radiation for electrical power. After a brief checkout period, Hawley released HST from the remote arm. Several brief thruster firings separated Discovery from its payload, and at last the Hubble Space Telescope was orbiting freely, 380 miles above the surface of Earth. The aperture door was opened 24 hours later. For approximately 2 months thereafter, the process of verifying and calibrating the performance of the telescope, spacecraft, and scientific instruments continued.

The first test images of a field of stars, so-called "first light" images, were taken with two Hubble cameras, the wide field and planetary camera (WFPC) and the faint object camera (FOC) on 20 May 1990. As these simple images of individual stars were displayed on a monitor, it was immediately evident to the astronomers and engineers present that the telescope was badly out of focus. Several mechanisms were available to diagnose and correct optical problems within the telescope. A technique called "phase retrieval analysis" applied to the camera images, as well as measurements by the telescope's fine guidance and wavefront sensor interferometers, provided an accurate indication of the aberrations inherent in the optical image. To improve the image quality, the telescope's secondary mirror could be tilted, moved off-center, and moved in and out to adjust alignment and focus. In addition the 2.4-meter primary mirror was mounted on 24 pressure pads that could be moved individually for small adjustments to the mirror's shape. These capabilities had been included in the design to provide flexibility to remove almost any type of optical aberration that might be induced as the telescope experienced the transition from “1 g” to the weightlessness of orbit. The one type of aberration that could not be corrected in this manner was the simplest and least likely—spherical aberration. The entire project team was therefore stunned by its own conclusions that the Hubble telescope was afflicted with spherical aberration and that it could not be corrected using any of the onboard optical or mechanical systems. On 21 June 1990 NASA announced publicly that the Hubble Space Telescope was not working properly.

Subsequent investigation (7) revealed that the grinding process at Perkin-Elmer had removed too much glass, by a very small amount, from the primary mirror. Although the surface of the mirror was exquisitely smooth, it was too flat—the error reached approximately 2.2 μm (about one-fiftieth the width of a human hair) at the outer radius. Consequently, light rays reflected from different concentric rings around the center of the primary mirror came to a focus at different locations (8). There was neither a single on-axis focal point, nor a single off-axis focal surface that defined the field of view. Instead, the focal points of different concentric rings were spread out across a range of 43 mm along the optical axis of the telescope. Rather than concentrating 70% of the light from a star in the central 0.1 arcsecond radius of its image as required, only 15% was contained in this tight central core. The remaining 85% of the light was widely dispersed in an “apron” around the central core of the image and was wasted. The error resulted from the improper assembly of a test device—a “reflective null corrector”—used to check the mirror's shape as the grinding process progressed. The error was evident in other, less precise test data, but these tests were discounted as unreliable themselves—in retrospect, a rationalization in an environment where the manufacturing process had fallen seriously behind schedule.

Despite intense criticism and negative publicity resulting from the announcement of Hubble's optical flaw, the HST program persevered in addressing the problem in several ways. First, the flaw itself was accurately characterized by both phase retrieval analysis of the astronomical images and by careful investigation of the reflective null corrector and other equipment with which the mirror had been manufactured at Perkin-Elmer. Even though the mirror had been ground to the wrong prescription, if one could accurately determine what that erroneous prescription was, it could be used to design highly effective corrective optics that might be incorporated in future HST scientific instruments. Several different diagnostic techniques gave the same, conclusive answer for the as-flown optical prescription (9).

Second, two instrument teams did incorporate this revised optical prescription in designs for instruments to be inserted into the telescope during the first servicing visit of Shuttle astronauts. Before HST's launch, a backup wide field and planetary camera (WFPC2) was already under development at NASA's Jet Propulsion Laboratory to ensure the observatory's long-term ability to acquire high-resolution wide-field images to meet its core scientific objectives. A relatively simple modification of small mirrors within WFPC2 would result in an accurate correction of the distorted telescope beam coming into the instrument. Concurrently, another team centered at the Space Telescope Science Institute and Ball Aerospace Corporation (10) invented an entirely new instrument called “COSTAR” (corrective optics for space telescope axial replacement). COSTAR contained pairs of small mirrors that could be inserted into the telescope beam to correct its spherical aberration before the beams passed through the entrance apertures of three other scientific instruments—the faint object camera (FOC), the Goddard high resolution spectrograph (GHRS), and the faint object spectrograph (FOS). These new optical designs would allow the telescope images to be sharply focused on the light-sensing detectors of WFPC2 and the other instruments. From the perspective of the scientific instruments, it would be as though spherical aberration had never occurred.

Third, although the image of a star or other "point source" was unfocused, it was very stable in the environment above Earth's atmosphere, and its shape could be accurately modeled. Even with spherical aberration, the image retained a very desirable property, a sharp central core that preserved some of the originally intended angular resolution. By applying a mathematical technique called "image deconvolution" (11), astronomers were able to remove the signature of spherical aberration partially from astronomical images, making it possible to implement a high-quality program of scientific observations during the early years of the mission before introducing corrective optics into the observatory (12-14). However, this early science was limited primarily to qualitative studies of relatively bright sources of minimal structural complexity. Hubble's highest priority objectives, including observing very faint objects far across the Universe and far back in time, observing individual stars in crowded fields, and performing quantitatively accurate measurements of an object's brightness, had to await the outcome of the first Hubble servicing mission.

On 2 December 1993, Space Shuttle Endeavor (STS-61) carried the first HST servicing crew into orbit (15-17). On board were the optically corrected WFPC2 and COSTAR, a new set of solar arrays redesigned to overcome spacecraft jitter induced by the original arrays, new gyros, equipment to augment the spacecraft's computer, and several other components needed to improve Hubble's performance. The stakes of this mission were high. It was widely viewed as a demonstration that astronauts in space suits could do the kind of complex and taxing work necessary to build the future International Space Station. It was a demonstration that NASA could overcome past mistakes and failures. And for astronomers, it was the last opportunity to realize Lyman Spitzer's dream. News media and the general public around the world closely followed the mission by nearly continuous television coverage. The outcome is properly characterized as heroic. Each of the five scheduled days of extravehicular activity (EVA) was successfully completed, and the astronaut crew returned safely to Earth on 13 December. Two weeks later at the Space Telescope Science Institute, the WFPC2 science team and other astronomers nervously awaited the "first light" picture of a rich field of stars and broke into cheers when the tightly focused images were first displayed. At a press briefing on 12 January 1994, one of the designers of COSTAR, James Crocker, declared that the optical quality of the repaired HST was "as good as modern engineering permits and the laws of physics allow" (18, 19). At that same briefing, Senator Barbara Mikulski of Maryland declared, "The trouble with Hubble is over!" In the years that followed, astronomers and the public as well were treated to the clearest and deepest views of the Universe ever experienced by humans—scenes of profound beauty and intellectual challenge.

Four fully successful servicing visits to Hubble have now been completed, encompassing 18 EVAs: SM2 (STS-82 on Shuttle Discovery) in February 1997 (20, 21), SM3A (STS-103 on Shuttle Discovery) in December 1999 (22), and SM3B (STS-109 on Shuttle Columbia) in March 2002 (23). These have significantly modernized the technology of Hubble's scientific instruments and spacecraft systems. Each mission has left the HST at least an order of magnitude more capable scientifically and far more reliable functionally—as though a "new" observatory had been created. One more servicing mission is planned for Hubble, after which it will be at the apex of its scientific capabilities. The Space Shuttle will retrieve Hubble and return it to Earth at the end of its operational life in 2010.

3. Observatory Design

The HST observatory is comprised of orbiting hardware—the telescope, the spacecraft, and a set of scientific instruments (Figure 2)—and computers, software systems, and teams of people on the ground that monitor and control the orbiting equipment and execute the Hubble science program. The ground-based operations of the HST are described later in this article. The heart of the observatory is the orbiting optical telescope (24). Its 2.4-meter (7.9-foot) aperture provides an unobstructed light collecting area of 40,000 cm^2. The telescope is a classical "Cassegrain" design. Light collected by the primary mirror is reflected to a secondary mirror 0.3 m in diameter, mounted 4.9 m forward of the primary. The secondary mirror in turn reflects the converging light beam back toward the primary. The beam passes through a "donut hole" 0.6 m in diameter in the center of the primary mirror and comes to a focus approximately 1.5 m behind the primary. This compact design folds the telescope of overall focal length 57.6 m into a package only 6.4 m long. The optical design of the telescope is also of a common type called "Ritchie–Chretien." The surface of each mirror has the shape of a hyperboloid. A Ritchie-Chretien telescope corrects the focused image for both spherical aberration and coma (image elongation) across the entire field of view. Its focal surface is curved and subject to astigmatism, however, and these forms of optical aberration must be corrected within the optical systems of the scientific instruments that share the focal surface. A system of baffles, painted flat black, are mounted around the outside of the primary mirror, around its central "donut hole," and around the secondary mirror, to attenuate stray or scattered light from bright, off-axis objects (e.g., the Sun, Moon, or bright Earth).

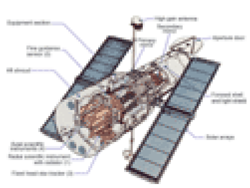

Figure 2. Cutaway schematic view of the major components of the Hubble Space Telescope.
[Full View]

The telescope is encapsulated in the Hubble spacecraft (Support Systems Module). A light shield with an aperture door and a forward shell protect the telescope from the harsh thermal environment, from micrometeoroids and space debris, and from stray light (including sunlight). Behind the forward shell is the equipment section, consisting of an annulus of bays that contain approximately 90% of the spacecraft's electronics, as well as the reaction wheels used to reorient the spacecraft from one pointing direction to another. At the back end of the spacecraft is the aft shroud that houses the focal plane assembly, the part of the optical telescope assembly's graphite-epoxy structure in which the scientific instruments are mounted. All of the spacecraft's interlocking shells, light shield, forward shell, equipment section, and aft shroud, provide a benign thermal and physical environment, cloaked in darkness, in which sensitive telescope optics and scientific instruments can operate properly for many years. The spacecraft is about 13.3 m (43.5 ft) long, excluding the open aperture door, and its widest diameter is 4.3 m (14 feet), excluding the solar arrays. Combined, the spacecraft, telescope assembly, instruments, and other equipment weigh about 11,100 kg (24,500 lb).

During its mission, the HST has had three different sets of solar arrays—two large, rectangular "wings" containing solar cells that convert sunlight to the electrical power needed to operate all of the orbiting hardware systems and to keep Hubble's six NiH_2 batteries charged for continuing operation during orbital night. The first two sets of arrays, provided by the European Space Agency, consisted of 48,760 silicon cells mounted on flexible blankets that could be unrolled somewhat like a window shade. The flexible design had the unintended effect of imparting small motions or "jitter" to the spacecraft resulting from sudden thermal flexure as it moved from the cold of orbital night to the heat of orbital day. Modifications of Hubble's pointing control software mitigated this problem for the first set of arrays, and an improved design of the second set of ESA arrays, mounted on the HST during the first servicing mission in 1993, led to even better performance. During Servicing Mission 3B in 2002, an entirely new solar array design was introduced into the HST. These are smaller, mechanically rigid array wings comprised of gallium arsenide (GaAs) solar cells that are approximately 30% more efficient in converting sunlight to electricity than the prior arrays. When new, these arrays provide approximately 5700 Watts of electrical power. They should amply meet Hubble's power needs to the end of its mission in 2010.

The exterior surface of Hubble experiences variations in temperature from –150 to +200°F in going from orbital night (Earth's shadow) to orbital day. Its orbit, inclined at an angle of 28.5° to the Earth's equator, precesses in space in a period of 55 days. So, the spacecraft goes through hot and cold seasons as Earth moves around the Sun and as the HST orbit precesses around Earth. Despite the harsh thermal environment, the interior of Hubble is maintained within a narrow range of temperature, in many areas at a "comfortable room temperature," by its thermal control system. Temperature sensors, electric heaters, insulation inside the spacecraft and on its outer surface, and paints that have special thermal properties all work in concert to keep the equipment inside the spacecraft at proper operating temperatures.

To avoid blurring Hubble's crystal clear images, the optical axis of the telescope must be tightly locked onto the selected astronomical target. Line-of-sight jitter is restrained by the spacecraft's pointing control system to approximately ±0.005 arcseconds rms during periods of 24 hours or longer. The full $\pm 3\sigma$ band of small motions, 0.030 arc seconds, corresponds to the angle subtended by a dime at a distance of 725 miles (1167 km), roughly the distance from Washington, D.C., to Chicago. Hubble must also be able to move from one target to another and place the new target within the aperture of a scientific instrument at an accuracy of 0.01 arcseconds. The exquisite pointing accuracy and stability are achieved by using a complex system of onboard sensors and actuators working together under the control of Hubble's central computer and pointing control system software. There is no propulsion system on the spacecraft. After completing observations at one pointing in the sky, the spacecraft is commanded to rotate in pitch, yaw, and roll, driven by adjustments to the spin rate (angular momentum) of motor-driven reaction wheels. There are four of these flywheels on board, rotating as fast as 3000 rpm; however, only three are required to move Hubble. During the slew to a new target, the change in orientation is measured relative to the orientation of three gyroscopes. These delicate and highly precise gyros also assist in stabilizing Hubble's pointing while it is acquiring and observing a celestial target. The spacecraft carries a total of six gyros to provide full redundancy because they have a limited lifetime. At the preprogrammed end of a three-axis slew the rotation of the reaction wheels is changed to brake the spacecraft's motion. Long electromagnets attached to Hubble's exterior interact with Earth's magnetic field to assist in controlling the angular momentum of the reaction wheels. The new pointing orientation is then determined by mapping a known field of stars using three star trackers. Finally, any two of three fine guidance sensors lock onto previously identified guide stars in the field of stars around the selected target. The fine guidance sensors are extraordinarily precise optical interferometers, capable of measuring the relative separations of stars in the sky to an accuracy of 0.002 arcseconds. They provide the ultimate degree of pointing stability to the telescope.

Commands to operate Hubble's suite of scientific instruments and digital data acquired from scientific observations with those instruments are routed through a command and data handling computer devoted to this purpose. Approximately 1.5 gigabytes per day of observational data are recorded onto either of two solid-state data recorders. The data are relayed through the spacecraft's two high-gain antennae to tracking and data relay satellites in geosynchronous orbit and from there to the TDRSS ground station at White Sands, New Mexico. The rate of production of scientific data from Hubble is expected roughly to double after the installation of new scientific instruments during the final servicing mission currently scheduled for 2005.

4. Hubble's Scientific Instruments

The HST can accommodate up to five scientific instruments. In addition, one of the three fine guidance sensors is designated as the primary instrument for astrometry—the science of precise measurement of the positions, motions, and distances of stars. NASA selected the first set of five Hubble instruments in 1977, and their designs reflected the technology of that era. The first set of instruments included a wide field and planetary camera, a faint object camera, a high-resolution spectrograph, a faint object spectrograph, and a high-speed photometer (25, 26).

Hubble's designers intended that it be serviced and upgraded periodically; astronauts would convey new components to orbit and install them during space walks (EVAs). Regular service calls would allow the instrument technology to remain current. Thus, it was envisioned that Hubble's scientific performance would evolve steadily, as technology permitted and as the progress of science demanded. Consequently, when the telescope's spherical aberration was diagnosed in 1990, NASA was well prepared to respond. All of the original instruments were affected by the poorly focused telescope image, some more adversely than others. In the first servicing mission in 1993, the wide field and planetary camera was replaced by an optically corrected instrument of similar design, which had been under development for several years before Hubble's launch. The high-speed photometer was removed from the observatory and replaced by COSTAR, the system of corrective optics that provided properly focused images to the two spectrographs and to the faint object camera. For the first time, these modifications allowed Hubble to achieve the level of scientific performance originally expected of it (27, 28). Replacement of instruments on subsequent servicing missions, in each case, resulted in order-of-magnitude gains in scientific performance. In effect, each servicing visit in which an instrument was replaced has left a "new," far more capable observatory in orbit.

In general, Hubble's instruments fall into two categories—cameras and spectrographs. The cameras acquire images taken through a variety of selectable filters chosen by astronomers to transmit light in a particular range of colors or wavelengths. They provide insight into the structure, brightness, color, and distance of celestial objects ranging from neighboring planets in our own solar system to clumps of protogalaxies so far away that the light we record was emitted when the Universe was less than 10% of its present age. Spectrographs provide data that, while far less pleasing to the eye, are centrally important to studying the physical properties of planets, stars, nebulae, and galaxies. Spectrographic observations allow astronomers to measure the temperature, density, velocity through space, velocity of rotation, and chemical composition of objects that either emit or absorb light. Taken together, these two classes of instruments provide a powerful toolbox for exploring the Universe.

The evolution of the capabilities of Hubble's scientific instruments since 1993 reflects the technological evolution of light-sensing detectors. Foremost are the solid-state silicon detectors called charge-coupled devices (CCDs). Such sensors are commonly found in commercial products readily available to consumers—digital still cameras and video cameras. The CCDs used in HST instruments differ from their commercial cousins only in their level of performance; they must be highly sensitive and have fine spatial resolution, wide dynamic range, and very low background noise. The HST mission pioneered the application of CCDs to astronomical imaging by flying an early generation of the detectors into space in the first wide field and planetary camera. The second wide field and planetary camera (WFPC2, pronounced "wiff-pik two"), launched in 1993, incorporated somewhat improved CCDs. In analogy to current consumer products, one can describe WFPC2 as a 2-megapixel digital camera. The advanced camera for surveys (ACS) carried to Hubble in the fourth servicing mission in March 2002 supplanted WFPC2 scientifically. The ACS is a 16-megapixel digital camera that has twice the field of view of the sky, twice the angular resolution, and five times greater sensitivity than WFPC2—dramatic improvements in scientific capability enabled by advances in CCD technology.

Figure 3. Astronauts John Grunsfeld and Richard Linnehan install a new exterior radiator, part of the NICMOS Cooling System, on the Hubble Space Telescope during Servicing Mission 3B in March 2002.

[Full View]

Both the WFPC2 and the ACS are sensitive to wavelengths of light shorter than about 1000 nm (1 μm). They are intended to view the Universe in the colors of the spectrum to which the human eye is sensitive and also at shorter ultraviolet wavelengths down to about 115 nm. However, much important research depends upon being able to observe at wavelengths longer than 1 μm in the range of colors that are "redder than red," called the near-infrared. Light emitted by galaxies at the most distant reaches of the Universe is "red-shifted" by the expansion of the Universe from visible wavelengths into the near-infrared band. Red and near-infrared light are also not as efficiently absorbed or scattered by particles of dust as light of shorter wavelength—yellow, green, or blue (this is why sunsets look redder when there is a lot of dust in the air). The universe is filled with dust, much of it so thick that human vision cannot penetrate, for example, the dusty cocoons in which new stars are born. The HST was designed to provide access to near-infrared light emitted by celestial sources, particularly in the 1–2.5 μm wavelength range.

Humans sense infrared radiation with their skin as heat rather than as light seen with the eye. Sensors used to detect these wavelengths are very sensitive to heat and must be cooled to extremely low temperatures and carefully baffled to avoid swamping the photons emitted by celestial sources by those emitted as heat by the warm telescope and its surrounding structures. Hubble's first infrared camera was the NICMOS (near-infrared camera and multi-object spectrometer), inserted into the spacecraft on the second servicing mission in February 1997. Its solid-state mercury-cadmium-telluride (HgCdTe) detectors, as well as its filters and a portion of its optics, were encased in a 108-kg block of solid nitrogen ice. The ice cooled the detectors to an operating temperature of 60 K (–213°C). Although NICMOS was designed to operate in this fashion for approximately 4 years, a small thermal leakage introduced excess heat into the solid nitrogen, which completely sublimated after about 23 months in orbit. An accelerated observing program acquired most of the astronomical observations originally intended for NICMOS (29). However, researchers, who hoped to follow up their original observations or to pursue new research programs with NICMOS, sorely felt the premature loss of Hubble's near-infrared "eyesight." Hubble Project engineers and scientists found an ingenious solution to the problem by adapting a high-technology mechanical cooler, developed jointly by NASA and the U.S. Air Force, to the task of cooling the dormant NICMOS instrument back to operating temperature. At the heart of this "reverse Brayton cycle" cryocooler are miniature turbines, approximately the diameter of a quarter in length, magnetically spun to very high rates, up to 7300 revolutions per second. This NICMOS cooling system (NCS) was installed during the servicing mission of 2002 (Figure 3). It successfully resuscitated the instrument to full operation and provided improved instrument performance because it allowed engineers to set the temperature of the HgCdTe detectors at a more optimal value (77 K) than possible by using the solid nitrogen cryogen.

Two of Hubble's original instruments were spectrographs designed to operate in complementary fashion. The faint object spectrograph (FOS) concentrated on relatively faint targets observed with low spectral resolution; the Goddard high-resolution spectrograph (GHRS) provided higher resolution spectra of brighter sources. (Spectral resolution simply describes how finely light spread out into its component colors is sub-divided into measurable increments of color or wavelength.) Both instruments used similar light-sensing detectors developed in the 1970s called "digicons"—one-dimensional arrays of about 500 individual silicon diodes. Although these were powerful detectors in their day, they significantly constrained the capabilities of these early instruments. The FOS and GHRS were limited to observing a single point at a time in the sky—a single star or small patch of an extended source such as a planet or galaxy. Neither could efficiently acquire data that spanned a wide band of wavelengths. In the 1980s, the advent of highly efficient two-dimensional detector arrays containing millions of pixels provided the opportunity to advance Hubble's spectroscopic power dramatically. In 1997, on the second HST servicing mission, astronauts replaced both the FOS and GHRS with a single, far more capable instrument—the Space Telescope imaging spectrograph (STIS). The three detectors in STIS—one CCD and two electronic sensors incorporating microchannel plate technology—together span the wavelength range from approximately 110 nm to 1 μm. For the first time on Hubble, a long entrance slit could be placed over an extended source, for example, across the nucleus of a galaxy, and the spectrum of each of 500 separate spatial points along the slit could be acquired simultaneously. This spatial and spectral multiplexing capability makes the STIS a prodigious hunter of supermassive black holes in galactic nuclei, for example. In a given exposure time, STIS can also acquire data across a wider range of wavelengths at a given spectral resolution—by as much as a factor of about 30—than either of its predecessors. In short, STIS is a thoroughly modern scientific instrument that well illustrates the potential to exhance the power of Hubble by modernizing its technology during in-orbit servicing (29).

Two new instruments are being developed as future additions to the HST observatory. The wide field camera 3 (WFC3) will replace WFPC2. It is designed as a "panchromatic" camera, encompassing both ultraviolet/optical and near-infrared imaging capabilities in a single instrument. The WFC3 complements the ACS by providing greater sensitivity and field of view in the near-ultraviolet (200–300 nm) and provides a backup to the ACS between 300 nm and 1 μm. In the near-infrared from 1 to 1.7 μm, WFC3 will supersede the NICMOS and has a substantially larger field of view, higher angular resolution, and far greater sensitivity. The cosmic origins spectrograph (COS) is designed to be the most sensitive spectrograph ever flown in space. Although, like FOS and GHRS, it is intended primarily to observe point sources of light, these include extremely faint objects far across the cosmos, for example, distant quasars.

5. Servicing the HST

The Hubble Space Telescope observatory represents an intersection of the Human Space Flight program with Robotic Space Flight. In this regard, it is unique among NASA programs. Although the financial cost of human involvement is relatively high, the rewards are demonstrably great. Hubble is arguably NASA's most successful space science program. It has given humanity a realistic opportunity to seek answers to ancient and far-reaching questions: How did the universe begin? How did it come to look the way it does? What is the universe made of? How has it changed with time? Where did we come from? What is our destiny? Hubble has also provided humanity's first truly clear view of the beauty of the cosmos, providing inspiration and aesthetic satisfaction to people from all walks of life. Without the intervention of space-walking astronauts, Hubble's original optical flaw would not have been repaired, and the mission would ultimately have been judged a scientific failure. Without regular human servicing, Hubble would have ceased operation long ago. Without human servicing, Hubble could never have been renewed technologically, and its original capabilities would now be viewed as archaic. So, the cost of servicing Hubble must be weighed against the total cost of a hypothetical program of multiple replacements of a failed or archaic observatory that had comparable capabilities, for which servicing by humans was not an option.

From the beginning, Hubble was designed to be “human-rated,” modular, and serviceable (Figure 4). Out of a total of 51major electrical, mechanical, and optical subsystems, only two—the primary telescope optics and the mechanical actuators that control their position or shape—are impossible for astronauts to replace or repair. Four fully successful Hubble servicing missions (as of 2002), encompassing a total of 18 fully successful space walks, have yielded a high level of experience and skill among the project engineers who design the missions and the astronauts who execute them (30). The pinnacle of this capability was reached in the fourth servicing mission in March 2002, when astronauts John Grunsfeld and Richard Linnehan successfully replaced a failing central power control unit on Hubble despite the fact that this heavily cabled box, the size of a small bookcase, was not designed to be easily removed from the spacecraft.

Figure 4. Hubble's new advanced camera for surveys acquired this image of the “Tadpole” galaxy shortly after it was launched in 2002. The long tail is the remnant of a collision between two galaxies, a small galaxy that has now been absorbed into the central region of a larger galaxy. This image astonished astronomers because of the great depth out to a large number of very distant galaxies it achieved in a small amount of observing time.
[Full View]

The Space Shuttle crew assigned to Hubble servicing missions consists of seven astronauts—a mission commander, a Shuttle pilot, an operator of the Shuttle's remote manipulator robot arm (RMS), and a team of four space-walking (EVA) astronauts. Typically, the EVA team is assigned 15–20 months before each mission. This allows sufficient time for thorough familiarization with Hubble, EVA procedure development, and extensive training. Accurate replicas of the Hubble spacecraft structures are situated in the Neutral Buoyancy Laboratory (NBL), a 40-feet deep, 6.2-million gallon swimming pool at the Johnson Space Center in Houston, Texas. There the astronauts can practice the choreography of every task of every space walk in an environment where the buoyancy of water simulates the weightless state they will encounter in space. Extensive crew training is also conducted at the Goddard Space Flight Center in Greenbelt, Maryland, where the crew practices removing and inserting the actual flight hardware that they will carry to orbit into high fidelity mechanical, electrical, and computer simulators of the Hubble spacecraft. The flight hardware is stored on carriers and within protective boxes in the Shuttle payload bay. The astronauts learn to remove the new flight components, including scientific instruments, from their carriers and to stow hardware removed from Hubble for the return journey to Earth. A large assortment of crew aids and tools—lights, tethers, handling brackets, foot restraints, and numerous manual and power tools—are developed to facilitate the EVA tasks and to minimize the time required and the physical stresses placed on the EVA astronauts. The training process is iterative in that, as the astronauts practice each task in the NBL or at Goddard, they often devise alternative procedures or recommend modifications of the tools and other hardware to improve the chances that each task can be successfully completed. Their ideas then become the basis for further improvements.

During each servicing mission, Hubble remains (with a few exceptions) powered on and operating even while physically attached to the Shuttle. Each EVA task must be coordinated with spacecraft operators at the Space Telescope Operations Control Center at Goddard, who also must be prepared to respond quickly and effectively to any unforeseen problems that arise as each EVA and the overall mission progresses. Before each mission, the teams at Goddard and Johnson, including the astronauts, conduct numerous dress rehearsals to practice every step of the flight. These joint integrated simulations involve practicing responses to plausible mission contingencies and emergencies that are often more dire than those typically experienced during an actual flight. In this way, the entire flight and ground-based operations team becomes skilled at complex problem solving—a major contributor to the apparent smoothness with which the actual missions are conducted.

A typical Hubble servicing mission lasts approximately 11 days, commencing with a spectacular launch of the Shuttle from Launch Complex 39A or 39B at the Kennedy Space Center in Florida. During the first two days of flight, the Shuttle crew initiates a number of thruster "burns" to adjust its orbit and to catch up gradually to the HST. On the third flight day, a final set of maneuvers brings the Shuttle within approximately 35 feet of the telescope. At the same time, ground controllers command HST to rotate so that its two grappling fixtures are properly oriented for capture by the Shuttle's robot arm. Once captured by the arm operator, Hubble is berthed and latched to a platform in the payload bay, somewhat akin to a "lazy Susan," which can be commanded to pivot and rotate to bring the various work sites on the spacecraft within easy reach of the EVA astronauts.

The core of each mission is the sequence of four or five EVAs carried out on successive days. Two EVA teams, each comprised of two astronauts, conduct their space walks on alternating days. The planned duration of each EVA is approximately 6 hours. However, it is not unusual for Hubble-servicing EVAs to extend as long as 8 hours. The ultimate limitations on EVA duration are set by spacesuit oxygen supplies, the degree of fatigue of the EVA team, and the time necessary to close down the work area and return to the airlock. During each EVA, one astronaut works from the end of the robot arm, attached to the RMS by foot restraints. The other astronaut works as a "free-floater," maneuvering around the payload bay with the assistance of tethers and handholds. The two exchange positions as the EVA progresses. The RMS operator inside the Shuttle cabin is a critical third member of the EVA team. He or she positions the astronaut attached to the arm with fine precision to allow opening Hubble's compartment doors, unplugging an instrument or other module, removing and stowing it elsewhere in the Shuttle payload bay, extracting new equipment from its protective enclosure or carrier and installing it within Hubble, followed by stowage of the old module for the return home. One unplanned EVA day is set aside in case it is needed to complete any unfinished tasks, and another unplanned EVA day is available to attend to any contingencies for final deployment of HST back into orbit or for preparing the Shuttle itself for reentry and landing. For example, if Hubble's aperture door should fail to open, astronauts could execute a "contingency EVA" to crank it open manually. The final 2–3 days of the flight provide an opportunity for the Shuttle crew to rest, to conduct other tasks unrelated to Hubble, and to prepare the orbiter for the return home.

To date (2002), four Hubble servicing missions have been completed. Servicing Mission 1 (SM1) in December 1993 was primarily oriented to correcting the telescope's optical flaw by installing WFPC2 and COSTAR. However, the astronauts also installed a new set of solar arrays, solar array drive electronics, new gyros, and additional memory and processing power for the spacecraft's central computer. They also made a simple repair to the Goddard high-resolution spectrograph.

In February 1997, Servicing Mission 2 (SM2) provided the first opportunity to concentrate on upgrading Hubble rather than simply repairing it. In this mission, two new, advanced technology instruments—the Space Telescope imaging spectrograph (STIS) and the near-infrared camera and multi-object spectrometer (NICMOS) were installed in the instrument bays from which the two first-generation spectrographs (FOS and GHRS) were removed. In addition, a new, solid-state digital data recorder replaced one of Hubble's old mechanical tape recorders, and a failing fine guidance sensor was replaced by a spare unit so that the former could be returned to the ground for refurbishing. Other replacements included a reaction wheel, a data interface unit, and solar array drive electronics. On this mission, the astronauts saw, for the first time, signs that the external thermal blankets covering Hubble's exterior were beginning to crack and peel. They reacted to this contingency, guided by engineers on the ground, by improvising some temporary thermal covers to patch the more severely degraded areas.

What had originally been planned as a single Servicing Mission 3 was split into two separate missions (SM3A and SM3B) when it was realized early in 1998 that Hubble's gyros were failing at an alarming rate. Mission 3A was quickly planned as a "contingency mission" to replace all of the spacecraft's six gyros. Three gyros must be working for Hubble to conduct science operations. Approximately six weeks before the launch of SM3A in December 1999, the fourth gyro failed, science observations by Hubble ceased, and the spacecraft was placed into a "zero-gyro" safemode until the astronauts arrived to make the repair. Advantage was taken of this unforeseen servicing opportunity to place a new, more capable central computer into the HST, to add a second digital data recorder, to replace a faulty radio transmitter, and to continue the round-robin change-out and refurbishing of the fine guidance sensors.

The most complex and difficult servicing mission to date was SM3B, launched in March 2002. The mission dramatically upgraded Hubble's scientific capabilities by the insertion of the advanced camera for surveys (ACS) and the NICMOS cooling system (NCS). In addition, the astronauts began the process of completely overhauling and updating the spacecraft's electrical power system by installing new, rigid, high-powered solar arrays and replacing the aging power control unit (PCU). Although the total list of EVA tasks on SM3B was shorter than that on prior missions, most of those tasks were more difficult and required much more EVA time to execute than on the previous three missions. SM3B was probably at the limit of what space-suited astronauts can physically accomplish, and this particular crew acquitted itself with glory.

At this time, a final servicing mission to Hubble is planned for 2005. Two new instruments (WFC3 and COS) will be installed, and a new thermal radiator will be mounted on Hubble's exterior to help keep the scientific instruments cooler during the latter years of the mission. The refurbishing and change-out of all three fine guidance sensors will be completed, the electrical overhaul of HST will be completed by replacing all six of its NiH_2 batteries, and a new set of six gyros will be installed. When the astronauts leave Hubble in orbit for the last time at the end of SM4, it will be at the apex of its capabilities—more powerful scientifically and more modern and robust technologically than at any time in its history. NASA currently plans to retrieve Hubble by using the Shuttle and to return it to the ground sometime around 2010.

6. Operating Hubble

Two categories of operations are necessary for Hubble, as for any space observatory—Science Operations and Spacecraft Operations. Science Operations translate the research plans of scientists into detailed sequences of specific commands to the internal electronics, detectors, and mechanisms of the scientific instruments and coordinates the execution of astronomical observations with the operations of the spacecraft. This coordination includes selecting of guide stars on which the fine guidance sensors will lock to hold the telescope steady during observations. It also specifies the timing of observations, to take into account when targets are blocked by Earth and cannot be seen during each 94-minute Hubble orbit, and when passage of Hubble through the most intense region of the van Allen radiation belts (the South Atlantic Anomaly) would degrade the observations. Spacecraft Operations control the functions of the spacecraft itself—loading commands into the onboard computers; pointing Hubble to the desired position on the sky and locking onto the guide stars; collecting and routing electrical power from the solar arrays; and storing digital data from the instruments, routing the data to onboard radio transmitters, and relaying the data to the Tracking and Data Relay Satellite System (TDRSS) for transmission to the ground. Spacecraft Operations also monitor all of the systems on Hubble to make sure that they are always operating properly, that Hubble remains "healthy" and "safe." If not, ground controllers intervene to remedy the problem, or in more serious contingencies, the spacecraft places itself into a protective "safe mode" to wait for troubleshooting and intervention from the ground. Both types of operations—Science and Spacecraft—must be seamlessly blended together 24 hours per day, every day of the year. The Space Telescope Science Institute (STScI) in Baltimore, Maryland, manages Hubble's Science Operations. The Hubble Operations Project at the Goddard Space Flight Center in Greenbelt, Maryland, is responsible for Spacecraft Operations, including all activities associated with Hubble's health and safety.

The Hubble observatory is operated as a "public facility." Once per year, astronomers from all over the world are invited to submit observing proposals for research that requires Hubble's unique capabilities. Typically, the amount of observing time requested on the telescope exceeds the total available time by factors of 6–8. Competition to use Hubble is intense, and many truly excellent scientific research proposals must be turned down each year. All proposals are peer-reviewed by panels of independent scientific experts who recommend to the Director of the Space Telescope Science Institute those proposals that have the most compelling scientific merit. The astronomers, whose proposals are selected, then provide very detailed descriptions of what they want the telescope to do—targets to be observed, instrument modes to be used, exposure times required, etc. A computer program at the STScI ingests these requests from all observers and produces a tentative calendar that extends months into the future, attempting to optimize the overall observing efficiency of the observatory. Celestial objects observed from Earth are frequently available only during particular seasons of the year. So, for example, the long-range planning calendar must take target availability into account. The detailed commanding plan for Hubble is laid out weekly. Approximately 11 days before the beginning of a specific week, the STScI delivers computer output to the spacecraft operators at Goddard that contains the detailed specifications and time line of commanded events for the science observations of that week. This “science mission specification” is then integrated into the overall spacecraft command plan for the week. During the week, the resulting spacecraft and instrument commands are uplinked and stored on board Hubble's computers several times per day. On average, about 15,000 stored commands are sent to Hubble each day. Direct control of Hubble from the ground to execute science observations is rare. The spacecraft is fully robotic and executes the preplanned science program autonomously under internal computer control.

During a single week, about 650 individual exposures on celestial targets are acquired. In October 2002, Hubble completed its 500,000th exposure. Currently, Hubble returns an average of 45 gigabytes of data to the ground each month. The data are received at Goddard, re-formatted and transmitted to the STScI. There, the data are processed, calibrated, archived, and distributed to the scientists who originally requested them. The scientists have a 1-year period during which their observations remain proprietary, so that they may be fully analyzed and interpreted. The results are usually published in professional scientific journals. After the 1-year proprietary period expires, the data become easily accessible to the remainder of the scientific community and to the public by direct access via the World Wide Web to the Hubble data archives at the STScI. Currently, the Hubble archives hold approximately 10 terabytes of scientific data, most of which are in the public domain.

7. Hubble's Scientific Achievements

The Hubble Space Telescope does not work in isolation. It is the flagship of a growing fleet of modern astronomical telescopes in space and on the ground. The unique power of the HST derives from its combination of extremely sharp images that cover relatively wide angular fields in the sky and have a deep dynamic range, low background noise, and sensitivity to wavelengths from the vacuum ultraviolet to the near-infrared. Most of Hubble's accomplishments build upon the previous work of ground-based and space astronomers over many decades. Hubble's greatest achievement is its facility for converting so many prior hypotheses, for which supporting empirical data were scant, ambiguous, and painfully difficult to obtain, into clearly and decisively demonstrated truth. But the HST has gone well beyond that. It has provided a detailed view of the unimagined complexity and diversity of the universe, as well as its startling beauty (31-34). It has yielded numerous surprises and raised new questions. With each new instrument inserted by the astronauts on servicing missions, Hubble grows in capability by factors of 10. It can reasonably be anticipated that Hubble's second decade will be at least as fruitful scientifically as its first. Some of the most important ways in which Hubble has influenced scientific thought follow.

7.1. Imaging the Distant Universe

The HST provided the first deep, clear view of the distant Universe from the approximately 150-hour exposure on the northern Hubble Deep Field in 1995 (35, 36). Only the COBE satellite has probed farther back in time, measuring the radiation left over from the Big Bang itself. The HST has shown that, when the Universe was very young, it was populated by structures that were much smaller and much more irregular in shape than the galaxies that we see in the modern Universe. It is believed that these smaller structures, made up of young stars and primordial gas, are the building blocks from which the more familiar spiral and elliptical galaxies were formed. However, the processes were complex, involving multiple galaxy collisions, in-fall of intergalactic gas, and the gravitational influence of supermassive black holes.

7.2. Precise Calibration of the Distance Scale

The HST 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. These distances were used in turn to recalibrate a number of other standard distance indicators such as Type Ia supernovae, which were applied in extending distance measurements to galaxies at much greater distances out into the "Hubble flow" where the relative velocities of galaxies are dominated by the expansion of the Universe itself. The result is a much more accurate measure of the rate at which the Universe is expanding (the Hubble constant) and a determination of the age of the Universe, that is, how long it had to have been expanding for galaxies to have reached the presently measured distances separating them (37). The initial calculation of the age of the Universe from Hubble data was based on the assumption that the expansion of the Universe is slowing down under the pull of the gravity exerted by all of the mass within it. In other words, the Universe was expanding more rapidly in the past than it is today. On this basis, the calculated age was 9–11 billion years, a value less than the independently estimated ages, for example, of the oldest stars in our own galaxy. This seemingly absurd contradiction was resolved only when it was determined that the expansion of the Universe is accelerating, rather than decelerating, at the present time, as discussed below.

7.3. Measuring the Cosmological Constant and the Age of the Universe

In its first decade, the HST partnered with ground-based telescopes in searching for and measuring the peak brightness and rate of change of brightness ("light curves") of Type Ia supernovae in distant galaxies whose light was emitted when the Universe was about half its present age (redshifts up to Z=1.2). Hubble's major contribution was accurate measurement of the most distant supernovae in this sample. From these measurements, the galaxies' distances could be accurately determined, and these values, combined with the measured recessional velocities of the galaxies, indicated the rate at which the Universe itself was expanding in various epochs far back in time. The result was remarkable and provided the first clue that the expansion of the Universe is accelerating at the present time—driven by an unknown repulsive form of gravity named "dark energy." Einstein anticipated such a possibility by adding a "cosmological constant" to his equations of general relativity because he believed that the Universe had to be static and would collapse under its own gravity if there were no repulsive force to compensate for ordinary gravity. After learning from Edwin Hubble that the Universe is observed to be expanding and thus, is not static, Einstein removed the cosmological constant from his theory, referring to it as his "greatest blunder." In 2001, the HST set the record for the most distant Type Ia supernova ever discovered (38). This supernova exploded when the universe was only one-third of its present age, and the HST's measurements show that the expansion of the Universe was still decelerating under the influence of ordinary gravity in that epoch. This discovery placed the evidence for the relatively recent transition of the expansion from deceleration to acceleration on far firmer ground by eliminating several alternative interpretations of the earlier observations of less distant supernovae, such as the possibility that their brightness is dimmed by intervening dust. If the Universe is currently accelerating, it took longer to reach its present size, and so is older than one would calculate from a simple measurement of the current value of the Hubble constant. The calculated age, properly corrected for acceleration, is 13–15 billion years—consistent with the ages estimated for the oldest stars (39). Currently, the accelerating universe and the nature of "dark energy" are considered among the most important and baffling problems in modern physics. Much future research must be done with the Hubble and other telescopes to "tease" clues about it out of the fabric of the Universe. The pursuit of "dark energy" may well produce a revolution in our understanding of the fundamental laws of physics.

7.4. Detecting and Measuring Supermassive Black Holes

Before the launch of the HST, ground-based images of galactic nuclei hinted at the existence of large concentrations of mass at the very centers of galaxies. Although it was suspected that these might be the massive black holes predicted theoretically as early as the 1930s, this was impossible to prove at the resolution of ground-based optical telescopes. The HST was the first optical telescope capable of probing sufficiently close to the center of a galaxy to measure spectroscopically the velocity of stars and gas in orbit around the central concentration and to measure accurately by directly imaging the size of the central cusp of starlight. Thus, in 1994, Hubble provided conclusive proof that a central black hole several billion times the mass of our Sun exists at the core of the giant elliptical galaxy M87. At about the same time, a ground-based microwave telescope measured the velocity of water masers in orbit around a black hole of several million solar masses in a different galaxy, thus providing further proof. The HST has now moved beyond the initial confirmation of the existence of supermassive black holes to a “demographic” survey of central black holes. Hubble has demonstrated that these powerful, enigmatic objects are found in the nuclei of most (or perhaps all) galaxies, whether or not those nuclei are energetically active. More profoundly, Hubble observations show that there is a very tight correlation between the mass of the central black hole in a galaxy and the mass of the surrounding ellipsoidal “bulge” of ordinary stars in which the black hole resides, whether observed in an elliptical galaxy or within the central bulge of a spiral galaxy like our own Milky Way. This relation is observed across the full range of black hole masses from one million to several billion times the mass of the Sun (40). Recently, Hubble observations provided the first evidence of possible intermediate-mass black holes thousands of times the mass of the Sun at the center of another type of ellipsoidal (spherical) system of stars—the globular star clusters that populate our own and other galaxies. The preliminary results indicate that these intermediate-mass black holes obey the very same relationship to the mass of the system of stars in which they exist as the supermassive black holes at the centers of galaxies. Mother Nature is providing a very strong clue here about the relationship between the formation of black holes and the formation of galaxies and other star systems—a clue that has yet to be deciphered.

7.5. The Nature of Quasars

For several decades, quasars (quasi-stellar radio sources), sometimes called QSOs (quasi-stellar objects), were among the most enigmatic objects in the Universe. When they were discovered in the 1960s, they were recognized as the most distant and energetic objects known. Continued study suggested a possible relationship between the quasars and another puzzling phenomenon—the highly active and energetic nuclei of certain galaxies at more moderate distances, the AGN (for active galactic nuclei). The detection of very faint “fuzz” around some quasars, seen with ground-based telescopes, supported the hypothesis that they might be very distant AGNs in the early Universe that are undergoing especially intense outbursts of activity. The HST has completely verified this idea (41). The telescope's resolution and dynamic range clearly reveal a variety of underlying host galaxies of quasars. A more surprising HST discovery is that a large fraction of quasar host galaxies appears to be in the process of colliding and merging with other galaxies. This suggests that galaxy collisions, which the HST has shown are common in the early Universe, may have provided the extra “fuel” to the massive central black holes in galaxies that is needed to generate the prodigious energy output of quasars and AGN. We know now that most or all galaxies possess massive central black holes, so it is assumed that those galaxies that are “quiet” at their nuclei, such as our own Milky Way, must be in a quiescent state, lacking a source of fuel, namely in-falling stars and gas.

7.6. The Origin of Gamma-ray Bursts

Intense bursts of highly energetic gamma radiation from unknown cosmic sources were first detected by military satellites. Thousands of these bursts were subsequently observed by the Compton Gamma Ray Observatory, which found that they are distributed more or less uniformly across the sky. Not only was the source of the bursts a mystery, it was not even known if they originated in our own galaxy, far across the Universe, or somewhere in between. The joint Italian-Dutch satellite 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 they were still bright. Using such "alerts" from Beppo-Sax, ground-based telescopes then located the gamma-ray sources in optical-wavelength light. Using this information, astronomers trained the HST on the optical counterparts of multiple gamma-ray bursts (42). Hubble's resolution and sensitivity gave it the unique ability to show that the sources of the gamma-ray bursts are embedded in faint, distant galaxies. Moreover, the optical light from the fading bursts in most cases emerges at random distances from the centers of these galaxies and is usually associated with regions undergoing episodes of intense massive star formation. The bursts do not appear to be associated with central black holes and active galactic nuclei. By following the brightness changes in the sources to very faint levels, the HST provides important constraints on models of the stellar "catastrophes" that produce these extraordinarily intense and rapid outbursts of energy. Today, at least two alternative explanations have been offered to explain the origin of gamma-ray bursts. Either an extremely massive star explodes, producing what has been dubbed a "hypernova" (implying explosive energy release far exceeding that of more common supernovae and perhaps concentrated in beams of radiation), or perhaps two neutron stars collide, forming a black hole. In the future, astronomers will attempt to select from among such alternative explanations on the basis of more detailed observations of the environments of gamma-ray bursts and also using measurements of the bursts themselves obtained closer to the moment of their peak brightness. The High Energy Transient Explorer (HETE-2) satellite, launched in 2001, now facilitates more rapid responses by Hubble and other telescopes to gamma-ray bursts.

7.7. The Birth of Stars

The HST's resolution and sensitivity to both visible and infrared light have given it unprecedented, clear views of the rich, diverse, and complex processes that lead to star formation. The collision of two galaxies, as clearly seen by the HST, stimulates the births of large populations of young, massive stars and star clusters (43). Compression of interstellar gas by the intense radiation from a massive star can trigger the formation of smaller stars nearby. It is seen that the radiation and ejected material from supernova explosions compress and enrich the interstellar gas and dust from which new stars can form. Stars forming in large, dense clouds of molecular hydrogen and dust are limited in the masses they can achieve by the erosion of material from those clouds by radiation from nearby hot stars. The formation of an individual star always seems to be governed by an accretion disk of material falling onto the young protostar and by highly aligned bipolar jets carrying material away from the "construction site." All of these processes have been clearly elucidated by Hubble observations (44).

7.8. The Formation of Planetary Systems

Before the HST, the presence of dust disks around a small number of young stars had been inferred from observations by infrared satellites, and a ground-based coronagraphic instrument had directly imaged one such disk around the star, beta Pictoris. For centuries, it has been believed that such a disk must have been the precursor to our own solar system, providing the raw material from which the planets were constructed. The existence of protoplanetary disks around other stars is, therefore, a necessary condition for the existence of extrasolar planetary systems. The HST has revolutionized this area of science. Images of the Orion nebula region obtained by Hubble (45) revealed that a large proportion of young stars (about 50%) is surrounded by gas and dust structures, many of which are clearly disks (Figure 5). High-resolution Hubble near-infrared images penetrating the dense dust of the Taurus dark cloud and other star-forming regions show protoplanetary disks in the process of formation and evolution (46). These disks are common and they contain enough material to form entire planetary systems equivalent to our solar system. HST coronagraphic observations revealed, for the first time, the internal structures of protoplanetary disks and debris left behind by prior planet formation (47). Hubble has also revealed the difficulties many stars may have in forming planetary systems because of the hostile environments in which they are born. Observations of the Orion nebula, for example, reveal that gas contained in protoplanetary disks may be quickly blown out of the disks by the intense radiation and fluxes of particles emitted by nearby massive, hot young stars. If a newly formed star the mass of our Sun, for example, is shaded by nearby clouds of dust, its surrounding protoplanetary disk will retain the hydrogen and helium gas needed to build gas-giant planets like Jupiter or Saturn. However, if the star is out in the open and exposed to the radiation of a nearby massive star, the formation of its gas-giant planets becomes a race against time—will new planets form before the necessary raw material has been blown away? The HST has opened this fertile new area of observational astronomy—the empirical study of the origin, structure, and evolution of protoplanetary systems.

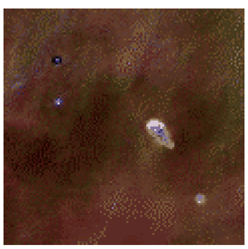

Figure 5. Three “proplyds” (for “protoplanetary disk”)—young stars surrounded by disks of dust and gas from which a system of planets might form—seen in the Orion Nebula. The “cocoon” shaped structures are envelopes of gas being blown out of the disk by the intense radiation from a nearby hot, young star. The disk seen in silhouette toward the upper left is apparently shaded from the hostile radiation environment and stands a better chance of forming a planetary system.
[Full View]

7.9. 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 and thus “seeds” the interstellar gas and dust with the basic building blocks from which new stars, planets, and life may form. The HST has provided exquisite images of dying stars. These are the basis for a remarkably detailed understanding of the events preceding the deaths of stars—how material is shed from dying stars, how that material interacts with the environment around the star, and how the process is influenced by each star's individual circumstances. Was the star single or part of a multiple star system, did it have planets, did it have a magnetic field, was it rapidly rotating, etc.? These factors determine the complex and incredibly beautiful structures of so-called “planetary nebulae”—the remnants of the outer layers of red giant stars which, having exhausted their thermonuclear fuel, become unstable and eject most of their mass into interstellar space. Only the star's core remains, a hot white dwarf whose intense radiation is absorbed by the ejected material, causing that material to glow. Stars like the Sun (and a bit more massive than the Sun) end their lives in this manner. The gentle ejection of planetary nebulae from such stars is the primary source of carbon in the Universe, the basis of our organic chemistry. The most spectacular example of a massive dying star is Hubble's imagery and spectroscopy of supernova SN1987a. For the first time, astronomers saw the delicate ring structures ejected during the preexplosive evolution of the dying star. They saw the blast debris expanding outward over time from the supernova explosion. Now they are seeing the innermost ring "light up" as the blast material plows into it (48).

7.10. Our Dynamic Solar System

The HST has obtained beautifully detailed images of the planets, satellites, comets, and asteroids of our own solar system (49) regularly for a period of years. It cannot rival the images taken by flyby spacecraft or orbiting probes like the Voyager or Galileo missions. However, HST complements these *in situ* missions because it can observe the entire solar system and follow changes across long periods of time by imaging and spectroscopy of exquisite quality. Hubble provided the first resolved images of Pluto and its satellite Charon, enabling measurement of their masses and crude mapping of their surfaces. HST imagery has shown that the atmospheres of the gas-giant outer planets, Uranus and Neptune, once thought to be bland and nearly featureless, possess very dynamic climates. Giant cloud patterns form and dissipate with regularity. The ultraviolet imaging capability of STIS and WFPC2 have given planetary scientists remarkable views of the northern and southern lights on Jupiter, Saturn, and Ganymede. Using Hubble, scientists have traced the dynamic electrical interactions between Jupiter and its satellite Io. In 1995, astronomers had the rare opportunity to view Saturn's rings edge-on. Hubble's sharp resolution led to the discovery of a diffuse atmosphere surrounding the rings, the discovery of several new satellites, and the recovery of old satellites in strange positions. The implication is that we are watching satellites of Saturn being created and destroyed nearly in "real time." The HST has monitored the weather on Mars and has provided remarkable images of seasonal changes at the Martian poles. In 1994, Hubble obtained uniquely clear pictures of the collisions of the 21 fragments of Comet Shoemaker-Levy/9 with the upper atmosphere of Jupiter and their aftermath (50). These revealed the enormous fireballs created when fragments entered the Jovian atmosphere at 140,000 miles per hour and heated the atmospheric gases up to 50,000°F, cooking them into a stew of "soot" and organic molecules (Figure 6). Studies of atmospheric waves propagating from the impact sites gave unique new information about the composition and density of Jupiter's atmosphere. The dispersal of the "soot" during several weeks allowed scientists to monitor the upper atmospheric winds. But the greatest contribution of the observing campaigns on Comet S-L/9 by the HST and by many other telescopes on earth was to remind humanity of our vulnerability as a planet and to motivate us to remain vigilant to the space environment in which we exist.

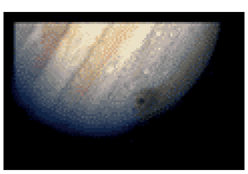

Figure 6. Impact zone of a large fragment of comet Shoemaker-Levy 9 in the atmosphere of Jupiter, as observed by Hubble in July 1994. The crescent pattern of "soot" floating high above Jupiter's cloud tops is roughly the diameter of Earth. [Full View]

7.11. The Unexpected

One measure of the impact of Hubble observations on scientific thought is the frequency with which scientific discoveries made using Hubble observations are cited by the authors of other papers in major scientific journals. In other words, how influential are the results from Hubble on the work of other scientists? Using this criterion, one can list in rank order those areas of research on which Hubble has made the greatest positive impact. Four of the top ten areas—galactic evolution (particularly from the Hubble Deep Field observations), the accelerating Universe, gamma-ray bursts, and dust disks around young stars—were either not known or were not expected to be subjects for major Hubble discoveries before the telescope was launched in 1990. This illustrates the great virtue of having available a powerful, versatile space observatory, regularly updated, maintained, and at the disposal of astronomers to address the most compelling scientific problems of the day, many of which were unanticipated only a few years previously. It is reasonable to expect that the Hubble Space Telescope will continue to compel us to address questions that we once did not even know how to ask for the remainder of its lifetime in orbit.

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