About the *Hubble Space Telescope*

Taken from: *Hubble 2006 Science Year in Review*

The full contents of this book include more Hubble science articles, an overview of the telescope, and more. The complete volume and its component sections are available for download online at:

[www.hubblesite.org/hubble_discoveries/science_year_in_review](http://www.hubblesite.org/hubble_discoveries/science_year_in_review)
Hubble’s History

Hubble’s remarkable mission has now spanned 16 years. During that time, it has been at the nexus of perhaps the most exciting period of discovery in the history of astronomy. At the same time, Hubble has offered up some of the most daunting challenges to humans working in space, and success in meeting those challenges has been among NASA’s greatest triumphs.

Since its launch in 1990, Hubble has been visited four times by astronauts to fix, restore, and upgrade its equipment. In nearly constant use between these servicing missions, Hubble has generated data for thousands of scientific papers, on topics ranging from discoveries of solar systems in formation, to precise measurements of the age of the universe.

The concept of a large telescope in space is as old as the space program itself. In a classified study in 1946, Lyman Spitzer first articulated the scientific and technical rationale for space astronomy. He continued to be the champion of the dream of a large telescope in space until it was realized. Supported by colleagues John Bahcall, George Field, and others, Spitzer was a tireless advocate within the astronomical community, to the public, and to the Federal Government. The outcome was a “new start” for the mission, authorized by Congress in 1977.

The technology needed for the Hubble Space Telescope was well advanced when work began. However, other serious technological and management challenges characterized the tumultuous years of Hubble’s design and manufacture. This turmoil culminated with the tragic loss of Space Shuttle Challenger and its crew in January 1986. Finally, against the backdrop of unrestrained anticipation by the public and the astronomical community alike, NASA launched Hubble into orbit on Space Shuttle Discovery (STS-31) on April 24, 1990.

Astronauts train to service Hubble in a huge, water-filled tank that simulates weightlessness. The astronauts wear pressurized suits similar to those they wear in orbit. They spend weeks doing this kind of training, and weeks in class. The astronauts also train using virtual reality, and in a chamber that mimics space temperatures of +200 to −200°F (+93 to −93°C). Here, astronauts practice replacing Hubble’s main computer—a task successfully accomplished during Servicing Mission 3A in December 1999.
Hubble’s first few months were disastrous. Instead of returning crisp, point-like images of stars, its images showed stars surrounded by large, fuzzy halos of light. The source of the problem was traced to an error in constructing the equipment used to test Hubble’s mirror during manufacture. Optical tests using this equipment led technicians to grind the mirror to the wrong shape, giving it a classic case of “spherical aberration.” The mirror was perfectly smooth, but would not focus light to a single point.

Hubble was designed to be visited by astronauts. Even before launch, NASA had begun to build a second-generation camera to replace the main camera that was launched with the telescope. Optical experts realized they could build corrective optics into the camera to counteract the flaw in the Hubble mirror. NASA accelerated work on the Wide Field Planetary Camera 2 (WFPC2), and Hubble scientists and engineers designed a mechanical fixture called Corrective Optics Space Telescope Axial Replacement (COSTAR) to deploy corrective optics in the light paths to the other instruments. In December 1993, astronauts returned to Hubble and undertook an ambitious set of space walks to install the new equipment. The modifications worked flawlessly, restoring Hubble’s image quality to nearly the original design goals.

In the decade following the first servicing mission, Hubble has treated astronomers and the public to the clearest and deepest views of the universe—scenes of profound beauty and intellectual challenge. Thousands of astronomers have used Hubble for boundary-breaking research in virtually all areas, from our own Solar System to the farthest depths of the expanding universe. Three additional servicing missions in 1997, 1999, and 2002 punctuated this era, and a final mission to upgrade and refurbish Hubble is planned for 2008.

The 1997 mission brought tremendous improvements to Hubble’s spectroscopic capabilities with the insertion of the Space Telescope Imaging Spectrograph (STIS). STIS observations not only demonstrated that black holes are ubiquitous in the centers of galaxies, but also showed that the black hole masses are tightly correlated with the masses of the surrounding ancient stellar population. The 1997 mission also opened Hubble’s view to the near-infrared universe with the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). The clear views of distant galaxies provided by NICMOS have supplied a wealth of clues to the complex physics in the early universe that led to the formation of the Milky Way.

Hubble was integrated at the Lockheed Martin Space Systems facility in Sunnyvale, California, where it appears in this pre-launch image. It is roughly the size of a subway car, 42.5 feet long, and 14 feet wide at its widest point. A close look at this image reveals a portion of the 225 ft. of yellow handrails installed around the outside for astronauts to grip during servicing mission spacewalks.
The servicing mission in 1999 enhanced many of Hubble’s subsystems, including the central computer, a new solid-state data-recording system to replace the aging magnetic tape drives, and the gyroscopes needed for pointing control. A month prior to launch, a gyroscope failure had forced Hubble into “safe mode,” with no ability to observe astronomical targets.

When a premature loss of solid-nitrogen coolant cut short NICMOS’s operational life, NASA engineers used innovative mechanical refrigeration technology to develop an alternate way of cooling its detectors to their operating temperature of −320º F. This cooling system was installed in 2002, and it brought the ailing instrument back to life. NICMOS has proved crucial to observations of very distant supernovae used to measure the acceleration of the universe. The 2002 mission also introduced Hubble’s most powerful camera, the Advanced Camera for Surveys (ACS), providing a tenfold improvement over WFPC2.

The final servicing mission in 2008 will install two new instruments, the Cosmic Origins Spectrograph (COS) and Wide Field Camera 3 (WFC3). COS is the most sensitive ultraviolet spectrograph ever built for Hubble. The instrument will probe the cosmic web—the large-scale structure of the universe—whose form is determined by the gravity of dark matter and is traced by the spatial distribution of galaxies and intergalactic gas. WFC3 is a new camera sensitive across a wide range of wavelengths (colors), including infrared, visible, and ultraviolet light. It will study planets in our Solar System, the formation histories of nearby galaxies, and early and distant galaxies beyond Hubble’s current reach. An attempt will also be made to repair the STIS. Installed in 1997, it stopped working in 2004. When repaired, the instrument will be used for high-resolution studies in visible and ultraviolet light of both nearby star systems and distant galaxies, providing information about the motions and chemical makeup of stars, planetary atmospheres, and other galaxies. Astronauts will also install a refurbished Fine Guidance Sensor to replace one degrading unit of the three already onboard. Two of these sensors are routinely used to enable Hubble’s precise pointing, and the third is available to astronomers for making accurate measurements of stellar positions.

The Hubble Space Telescope, operating at the intersection of the robotic and the human space flight programs, embodies both the trials and triumphs of the space program. It has survived controversy, delays, and failures, and has proven to be one of the most powerful and productive scientific tools ever developed.

_Hubble_ wasn’t assembled in a day. Neither was this _Hubble_ image of the face-on spiral galaxy Messier 101 (M101). Using the power of the Advanced Camera for Surveys installed during the last servicing mission to the satellite, it is the largest and most detailed photo of a spiral galaxy that has ever been released from _Hubble_. The galaxy’s portrait is actually composed of 51 individual exposures, in addition to elements from ground-based telescope images.
ACS
ACS is a so-called third generation Hubble instrument. Its wide field of view is nearly twice that of Hubble's previous workhorse camera, WFPC2. The name, Advanced Camera for Surveys, comes from its particular ability to map relatively large areas of the sky in great detail.

NICMOS
The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) is an instrument for near-infrared imaging and spectroscopic observations of astronomical targets. NICMOS detects light with wavelengths from 800 to 2500 nm.

FGS
Hubble has three Fine Guidance Sensors on board. Two of them are needed to point and lock the telescope on the target and the third can be used for stellar position measurements, also known as astrometry.

STIS
The Space Telescope Imaging Spectrograph (STIS) is currently not operating, but is a versatile multipurpose instrument taking full advantage of modern technology. It combines a camera with a spectrograph and covers a wide range of wavelengths from the near-infrared region into the ultraviolet.

COSTAR
The Corrective Optics Space Telescope Axial Replacement (COSTAR) is not really a science instrument: it is the corrective optics package that replaced the High Speed Photometer (HSP) during the first servicing mission. COSTAR was designed to correct the effects of the primary mirror's aberration.

Primary mirror
Hubble's primary mirror is made of a special glass coated with aluminium and a special compound that reflects ultraviolet light. It is 2.4-m in diameter and collects the light from stars and galaxies and reflects it to the secondary mirror.

The Hubble Space Telescope
Solar panels

Hubble's third set of solar arrays produces enough power to enable all the science instruments to operate simultaneously, thereby making Hubble even more efficient. The panels are rigid and unlike earlier versions, do not vibrate, making it possible to perform stable, pinpoint-sharp observations.

Secondary mirror

Like the primary mirror, Hubble's secondary mirror is made of special glass coated with aluminum and a special compound to reflect ultraviolet light. It is .33-m in diameter and reflects the light back through a hole in the primary mirror and into the instruments.

Communication antennae

Once Hubble observes a celestial object, its onboard computers convert the image or spectrum into long strings of numbers that, via one of Hubble's two high-gain antennae, are sent to one of the satellites that form the Tracking and Data Relay Satellite System (TDRSS).

Support systems

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

WFPC2

WFPC2 was Hubble's workhorse camera until the installation of ACS. It records excellent quality images through a selection of 48 color filters covering a spectral range from far-ultraviolet to visible and near-infrared wavelengths. WFPC2 has produced most of the stunning pictures that have been released as public outreach images over the years.
Observatory Design

About the size and weight of a subway car, *Hubble* owes much of its design to the legacy of the Cold War, being in many respects a copy of a KH-11 reconnaissance satellite. *Hubble* is just one of roughly a dozen large telescopes of similar design that have been lofted into orbit—but *Hubble* was designed to look up, not down.

The heart of *Hubble* is its 2.4-m mirror. While small by the standards of ground-based observatories, this mirror collects about 40,000 times as much light as the human eye, and its location above the distorting effects of the Earth’s atmosphere allows *Hubble* to obtain very sharp images and view wavelengths of light that do not reach the Earth’s surface.

*Hubble* has an optical layout known as a Ritchie-Chrétien Cassegrain design. The incoming light bounces off the primary mirror, up to a secondary mirror, and back down through a hole in the primary mirror, where it comes to a focus on a set of “pickoff” mirrors that guides the light to the scientific instruments. A graphite-epoxy truss provides a rigid structure for the main optics, and a system of baffles painted flat black is mounted within the telescope to suppress stray or scattered light from the Sun, Moon, or Earth.

*Hubble* is encased in a thin aluminum shell, blanketed by many thin layers of insulation to reduce temperature fluctuations. The telescope itself is housed in the narrower top section of the tube. Most of the control electronics sit in the middle of the telescope, where the tube widens. The middle section also houses *Hubble*’s four 100-pound reaction wheels. *Hubble* reorients itself around the sky by exchanging momentum with these spinning flywheels. Astronauts can easily access the devices in *Hubble*’s midsection, and a number of these have been replaced or upgraded during servicing missions. At the back end of the spacecraft, the “aft shroud” houses the scientific instruments, gyroscopes, star trackers, and other components. All of

The *Hubble Space Telescope* floats against the background of Earth after a week of repair and upgrade by Space Shuttle *Columbia* astronauts in 2002. *Hubble*’s fourth servicing mission gave the telescope its first new instrument installed since the 1997 repair mission—the Advanced Camera for Surveys. It has twice the field of view and records information much faster than *Hubble*’s Wide Field and Planetary Camera 2.
the spacecraft’s interlocking shells—the 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. Excluding the aperture door and solar arrays, *Hubble* is about 43 ft long and 14 ft in diameter at its widest point. Altogether, it weighs about 25,000 pounds.

*Hubble*’s electrical power comes from two 25-foot-long solar panels, which are mounted like wings on the side of the observatory and rotate to point toward the Sun. Six batteries, charged by solar power when the Sun is overhead, provide power when the Earth blocks the Sun. Astronauts replaced the solar arrays on two occasions during servicing missions. The present arrays are rigid panels of gallium arsenide cells that were originally designed for commercial communications satellites. They are about 30% more efficient in converting sunlight to electricity than the prior arrays. When new, they generated about 5,700 W of electrical power.

Workers study *Hubble*’s main, 8 ft. (2.4-m) mirror prior to launch. Its concave shape focuses the light it collects to form an image, which is then examined by *Hubble*’s instruments.

The next great *Hubble* camera, the Wide Field Camera 3 (WFC3), will be the first on *Hubble* to provide wide-field, high-resolution images at wavelengths from the ultraviolet to the near infrared (200-1700 nm).
In a single orbit around Earth, the exterior surface of Hubble varies in temperature from −150°F to +200°F. Despite the harsh thermal environment, the interior of Hubble is maintained within a narrow range of temperatures—in many areas at a “comfortable room temperature”—by its thermal control system. Temperature sensors, electric heaters, radiators, insulation inside the spacecraft and on its outer surface, and paints that have special thermal properties all work in concert to minimize the expansion and contraction that could throw the telescope out of focus, and to keep the equipment inside the spacecraft at proper operating temperatures. In addition to guiding the telescope, the fine guidance sensors are used to make very precise measurements of the relative positions of stars, which is essential for estimating distances to nearby stars or masses of components of binary star systems.

The aft shroud has room for five scientific instruments. Over the years, NASA and ESA have manufactured 12 scientific instruments for Hubble. Each new generation of instruments has brought enormous improvements to the scientific capabilities of the observatory through advances in technology. Many of Hubble’s discoveries with these new instruments would have been impossible to achieve with the instruments installed at launch.
Operating *Hubble*

The Sun and Earth rise and set for *Hubble* two times in three hours, as the spacecraft skims the upper atmosphere at an altitude of 360 miles. The looming Earth blocks half the sky and regularly interrupts most observations by blocking the line of sight to the target.

Because *Hubble’s* slew rate from target to target is only about as fast as the minute hand on a watch, it cannot keep ahead of this game. Nevertheless, careful scheduling keeps *Hubble* gathering light from stars and galaxies almost 50% of the time.

It is the job of *Hubble* controllers at the Space Telescope Science Institute and NASA’s Goddard Space Flight Center to seamlessly blend science operations and spacecraft operations 24 hours a day. Scientists and engineers at the Institute translate the research plans of astronomers into detailed sequences of commands for the internal electronics, detectors, and mechanisms of the scientific instruments. The preparations, carried out weeks or months in advance of the observations, also involve selecting guide stars to stabilize the telescope pointing, and specifying the exact sequence and timing of the observations. Spacecraft controllers work together to schedule *Hubble’s* communication with the ground, to load commands into the onboard computers, to manage the collection of electrical power from solar arrays and batteries, and to curate the data in the onboard computers. The flight operations team at Goddard monitors every system on *Hubble* to ensure it is working properly. If not, ground controllers can intervene to remedy the problem.

Over the past year, *Hubble* pursued its usual wide range of scientific programs, targeting objects ranging from nearby planets to galaxies billions of light-years away. Among the most technically challenging observations were those aimed at a member of the Solar System, comet Schwassmann-Wachmann 3. Discovered photographically by Arnold Schwassmann and Arno Arthur Wachmann of Hamburg Observatory on May 2, 1930, as it was passing within 6 million miles of Earth, the
comet has a relatively short orbital period of 5.45 years. The 1995 apparition provided fireworks, as the nucleus broke into four fragments and the comet brightened over hundredfold in a series of outbursts. This display was driven by outgassing from volatiles in the cometary nucleus evaporated by solar heating, rather than external tidal forces imposed by the Sun or Jupiter. In 2001, two components of Schwassmann-Wachmann 3 were still visible.

In preparation for its return in 2006, a team of astronomers led by Phillippe Lamy of Laboratoire d’Astronomie Spatiale in France and Harold Weaver of the Johns Hopkins University, put together a proposal to use the Advanced Camera for Surveys (ACS) on Hubble to obtain detailed multicolor images of the disintegrating nucleus. The proposal was submitted to the Institute in January 2006, along with hundreds of other Phase I proposals from around the world requesting Hubble observing time.
Two important *Hubble* simulators are located in the large “high-bay” area of Building 29 at the Goddard Space Flight Center. The Vehicle Electrical System Test (VEST) unit in the foreground electrically simulates the many complex components of the satellite. The High Fidelity Mechanical Simulator located behind it is used for “fit checks” of new hardware (such as instruments or gyroscopes) and for astronaut training.

In a process used in the 13 previous cycles, proposals were carefully reviewed by a peer committee of other scientists in the *Hubble* Cycle 14 time allocation process. The Lamy-Weaver proposal was awarded nine orbits. Working with scientists at the Institute, the team then developed a Phase II proposal, which specified the exact sequence of color filters, exposure times, and positions to catch the comet near its closest approach to Earth—four tenths of the distance between Earth and the Sun.

For most observations, *Hubble* locks on distant “guide” stars in its Fine Guidance Sensors to steady itself as it takes exposures. Because Schwassmann-Wachmann 3 was moving against the background stars, *Hubble* had to continuously reorient itself to track the comet, changing guide stars, and sometimes relying on just a single guide star.
Schwassmann-Wachmann 3 proved to be unexpectedly active, and a major outburst developed as it approached the prime viewing zone. Consequently, the team applied to the Institute director and received an additional allocation of his discretionary time to obtain more coverage of the unfolding events.

_Hubble_ observations are scheduled on a weekly basis. Individual observations are coded as a series of commands that are uplinked and stored onboard _Hubble_, instructing the telescope where to point, acquire guide stars, and initiate exposure sequences with specific instruments. The first nine orbits of exposure time were obtained over April 10–11, 2006. The follow-on observations occurred on April 18–20.

The images were temporarily stored in solid-state memory within _Hubble_ and then downlinked via a NASA communications satellite to a ground terminal in White Sands, New Mexico. From there, the data were transferred to Goddard Space Flight Center in Greenbelt, Maryland, and then to the Institute in Baltimore, where the images were stored in the _Hubble_ data archive.

At the same time, an automatic e-mail message was sent to the Principal Investigators, informing them that the images were available as fully processed images, reduced using the standard calibration pipeline, and as raw images for customized processing, if desired.
The Schwassman-Wachmann 3 observations showed that the cometary nucleus had degenerated into a chain of more than three dozen small fragments. *Hubble* had provided a ringside seat—and a wealth of detail inaccessible to ground-based telescopes—for the demise of a disintegrating comet.

Moving well beyond the Solar System, *Hubble* observations continue to play a crucial role in probing the cosmic flow of galaxies, finding evidence for a mysterious dark energy that pervades the universe. Type Ia supernovae have emerged as “standard candles,” enabling measurements of large cosmic distances and providing a basis for observational cosmology. Triggered by the disruption of compact white dwarf stars in binary systems, these supernovae are vast explosions that, at their brightest, outshine a galaxy. Because these events are unpredictable and relatively short lived, astronomers must adopt clever strategies to detect them and measure their brightness variations to determine their distance. Saul Perlmutter, at Lawrence Berkeley Laboratory, and Adam Riess, at the Institute and the Johns Hopkins University, have been using the ACS to survey distant galaxies for suitable supernovae. These programs require particularly intense data analysis, because supernovae fade on timescales of days. Typically, the wide-field ACS observations are taken from the archive, processed, and thoroughly scrutinized for new supernovae within 24–36 hours of their being taken. This rapid turnaround is essential to allow follow-up observations with the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) before the supernova fades into obscurity. The NICMOS observations, added to the observing schedule over the next 1–3 weeks as target-of-opportunity observations, map the decline in the supernova’s brightness—its “light curve.” The shape of that light curve allows *Hubble* to measure the distances accurately enough to reveal the acceleration of the universe at great cosmic distances.

*Hubble* provided astronomers with extraordinary views of comet 73P/Schwassmann-Wachmann 3. The fragile comet rapidly disintegrated as it approached the Sun. *Hubble* images uncovered many more fragments than were reported by ground-based observers. These observations facilitate the opportunity to study in detail the demise of a comet nucleus.
Hubble News

*Hubble* observations have produced a regular stream of news about the universe. Shown here are a few recent highlights. Details on these topics and many others can be found on the World Wide Web at http://hubblesite.org.

Recently discovered supernovae in distant galaxies support the theory that an unknown, i.e., “dark” energy has influenced the universe for at least the last 9 billion years. Using the light from the supernovae as “standard candles,” astronomers have measured the relative size of the universe over time and derived its expansion rate. This, in turn, helps in describing the forces at work controlling the expansion.

Intricate wisps of glowing gas float amid a myriad of stars in this *Hubble* image of the supernova remnant, N132D. The ejected material shows that roughly 3,000 years have passed since the supernova blast. This titanic explosion took place in the Large Magellanic Cloud, a neighboring galaxy some 160,000 light-years away.
(Opposite Page, Top Left) NASA’s Hubble Space Telescope has uncovered what astronomers are reporting as the dimmest stars ever seen in any globular star cluster (shown circled in the right-hand panels). Globular clusters are spherical concentrations of hundreds of thousands of stars within a galaxy. The cluster NGC 6397 is one of the closest globular clusters to Earth. Seeing the whole range of stars in this area will yield insights into the age, origin, and evolution of the cluster.

(Left) Dark matter and normal matter have been wrenched apart by the tremendous collision of two large clusters of galaxies. Hot gas detected by Chandra in x-rays is seen as two pink clumps in the image and contains most of the “normal” matter in the two clusters. The blue areas are the regions where the dark matter is clumped—as determined by the study of the distorted (gravitationally lensed) galaxy shapes in these areas.

(Right) Precision measurements taken over a seven-year period of the positions of core stars within the globular cluster 47 Tucanae have confirmed that gravitational segregation by mass is occurring within the cluster. The heavier stars are slowing down and sinking to the cluster’s core, while the lighter stars are picking up speed and moving to its periphery.
(Top Right) Long-duration gamma-ray bursts are powerful flashes of high-energy radiation that are sometimes seen coming from certain types of supernovae. If Earth were hit by such a nearby burst, the devastation could range from destroying the ozone in our atmosphere to triggering climate change. These images are a sampling of the host galaxies of long-duration bursts taken by Hubble. Astronomers analyzing these surveys have concluded that our Milky Way galaxy is an unlikely place for them to occur. The green crosshairs pinpoint the location of the gamma-ray bursts, now long faded away.

(Left) These dark, opaque knots of gas and dust are called “Bok globules.” They are absorbing light in the center of the nearby emission nebula and star-forming region, NGC 281. These images were taken with Hubble’s Advanced Camera for Surveys. NGC 281 is located nearly 9,500 light-years away in the direction of the constellation Cassiopeia.