About the Hubble Space Telescope

- Hubble's History
- Observatory Design
- Operating Hubble
- 20th Anniversary
- The Making of the Hubble IMAX 3-D Movie
- Hubble News

Taken from:
*Hubble 2010: Science Year in Review*


The full contents of this book include *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

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

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

A tireless advocate of space astronomy, Spitzer was joined in the 1970s by colleagues John Bahcall, George Field, and...
others to champion the concept within the astronomical community, to the public, and to the Federal Government. Finally, Congress authorized the mission in 1977.

Serious technological and management challenges—including funding and scheduling issues—arose in the turbulent years of Hubble’s design and manufacture. After extensive testing, Hubble was in the final stages of preparation for launch aboard the Space Shuttle, when, in January of 1986, the nation suffered the loss of the Space Shuttle Challenger and its crew due to a flaw in the design of the Shuttle’s solid rocket boosters. Nearly three more years would pass before reengineered shuttle flights resumed and the dream of a working telescope in space could be realized. On April 25, 1990, the astronauts of the STS-31 mission deployed Hubble into orbit from the Space Shuttle Discovery with every expectation that stunning new views would result.

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

Although engineers designed Hubble with many replaceable components, the primary mirror was not one of them. However, the ability for astronauts to upgrade the observatory on orbit ultimately led to a solution for this seemingly insurmountable problem. Even before NASA launched Hubble, engineers were hard at work building an improved, second-generation camera—the Wide Field Planetary Camera 2 (WFPC2)—meant for installation by astronauts at a future date. Optics experts realized they could build corrective optics into this camera to counteract the flaw in the primary mirror.

Meanwhile, Hubble scientists and engineers devised a set of nickel- and quarter-sized mirrors to remedy the effects of the primary mirror on Hubble’s other instruments. Called the Corrective Optics Space Telescope Axial Replacement (COSTAR), this device would be deployed into the light paths of the telescope’s other instruments to focus their images properly. In December 1993, astronauts installed COSTAR during a series of spacewalks. The ambitious endeavor restored Hubble’s vision to original expectations. In the 17 years following that historic, first servicing mission, Hubble has amassed a
spectacular treasure trove for scientists—thousands of clear, deep views of the universe. Astronomers from around the world have used the telescope to answer some of the most pressing astronomical questions of our time, and its discoveries have also spawned a host of follow-up investigations.

As new technology became available, Hubble’s innovative, modular design enabled it to be upgraded and enhanced through four additional servicing missions. In 1997, Servicing Mission 2 vastly improved Hubble’s spectroscopic capabilities with the insertion of the Space Telescope Imaging Spectrograph (STIS). STIS confirmed the existence of supermassive black holes in the centers of galaxies and also showed that black hole masses are tightly correlated with the masses of the surrounding ancient stellar population. During the 1997 service call, NASA also opened Hubble’s view to the near-infrared universe with the addition of the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). This instrument helped untangle the complex processes in the early universe that led to the formation of galaxies, including our own Milky Way.

During Servicing Mission 3A in 1999, spacewalking astronauts enhanced many of Hubble’s subsystems—replacing its central computer, adding a new, solid-state data-recording system to replace its aging magnetic tape drives, and swapping out the gyroscopes needed for pointing control. When a premature loss of solid-nitrogen coolant cut short NICMOS’s operational life, engineers devised innovative mechanical refrigeration technology as an alternate way of cooling its detectors to their operating temperature of −320°F (−196°C). On Servicing Mission 3B in 2002, this cooling system was retrofitted to NICMOS, which brought the instrument back to life. During that mission, astronauts also installed a new, more powerful camera—the Advanced Camera for Surveys (ACS)—providing a tenfold improvement over WFPC2.
In 2009, Servicing Mission 4 (SM4)—the final servicing mission to Hubble—brought the telescope to the apex of its scientific capabilities. Astronauts installed two new instruments: the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3 (WFC3). COS is the most sensitive ultraviolet spectrograph ever built for Hubble. It probes the cosmic web—the large-scale structure of the universe—whose form is determined by the gravity of dark matter and is traced by the spatial distribution of galaxies and intergalactic gas. WFC3 is sensitive across a wide range of wavelengths (colors), including infrared, visible, and ultraviolet light. It contains a variety of broad- and narrow-band filters, as well as grisms (spectroscopic elements), which enable wide-field, low-resolution, slitless spectroscopy with unparalleled sensitivity. WFC3 studies planets in our solar system, the formation histories of nearby galaxies, and early and distant galaxies.

Astronauts also made in-orbit repairs to two instruments already on Hubble: STIS and ACS. Neither was designed to be serviced in space, so both repairs required new tools and procedures. STIS had stopped working in 2004; to recover it, astronauts replaced a low-voltage power supply board. ACS had suffered a partial failure in early 2007 after operating exquisitely for nearly five years. To fix it, astronauts replaced failed circuit boards and added a new power supply. These steps effectively restored its high-efficiency imaging in both the visible and ultraviolet portions of the spectrum. Rounding out the mission, various aging components of the spacecraft were upgraded, including the gyroscopes and batteries.

A study in travail and triumph, the Hubble Space Telescope brings together the best of NASA’s robotic and human space flight programs. One of the most powerful and productive scientific tools ever developed, Hubble captures scenes of profound beauty and intellectual challenge. Thousands of astronomers have used Hubble for boundary-breaking research in virtually all areas, including determining the age of the universe and the existence of supermassive black holes. Hubble discoveries have also led to a series of new questions, such as those surrounding the accelerating expansion rate of the universe and the existence of dark energy. Not since the days of Galileo has a telescope provided such insight and piqued the curiosity of the human race so completely.

Originally called the Large Space Telescope, NASA renamed the observatory in honor of astronomer Edwin P. Hubble. Hubble’s observations from Mount Wilson in the early 20th century established that galaxies are located at great distances outside our own. Along with fellow astronomer Milton Humason, he also discovered a relationship between the distance to a galaxy and its spectral redshift that provided fundamental evidence that the universe is expanding. Hubble is honored throughout the world for his accomplishments. This bronze bust is displayed in the State Capitol of Missouri, his home state. (Photo credit: Tim Bommel, Missouri House of Representatives)
The Hubble Space Telescope
The Hubble Space Telescope

1. **Primary mirror**
Hubble’s 2.4 meter-diameter primary mirror is made of a special glass coated with aluminum and a compound that reflects ultraviolet light. It collects light from the telescope’s targets and reflects it to the secondary mirror.

2. **Secondary mirror**
Like the primary mirror, Hubble’s secondary mirror is made of special glass coated with aluminum and a compound to reflect ultraviolet light. It is 0.33 meters in diameter and reflects the light back through a hole in the primary mirror and into the instruments.

3. **Aperture door**
Hubble’s aperture door can close, if necessary, to prevent light from the Sun from entering the telescope.

4. **Communication antennas**
Data stored in Hubble’s solid-state recorder is converted to radio waves and then beamed through one of the spacecraft’s high-gain antennas to a NASA communications satellite, which relays it to the ground. Because they would extend out of the image above and below the spacecraft, the antennas are shown here pressed against the side of the telescope in their “berthed position.” This is how they are configured when Hubble is serviced by the astronauts in the payload bay of the Shuttle.

5. **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. Unlike earlier versions, the panels are rigid, helping the observatory stay even more stable than before.

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

7. **WFC3**
During SM4, astronauts installed Wide Field Camera 3 (WFC3), replacing the Wide Field Planetary Camera 2. With panchromatic vision extending from the ultraviolet through the visible and into the infrared, WFC3 enhances Hubble’s capability not only by seeing deeper into the universe, but also by providing wide-field imagery in these three regions of the electromagnetic spectrum. WFC3 is essential to the study of galactic evolution, star populations in nearby galaxies, dark energy, and dark matter.

8. **ACS**
The Advanced Camera for Surveys is designed primarily for wide-field imagery in the visible wavelengths, though it also sees in ultraviolet and near infrared. When its wide-field and high-resolution channels failed in 2007, the solar-blind channel—which observes in far-ultraviolet wavelengths—remained operational. Astronauts performed an on-orbit repair during Servicing Mission 4 (SM4) that restored the wide-field channel, which performs surveys of the universe. The high-resolution channel could not be recovered, but the wide-field channel and solar-blind channel are now operational.

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

10. **COS**
Astronauts installed the Cosmic Origins Spectrograph during SM4 in place of the Corrective Optics Space Telescope Axial Replacement (COSTAR). The most powerful ultraviolet spectrograph ever flown, COS measures the structure and composition of the ordinary matter concentrated in the “cosmic web.” It also studies how galaxies, stars, and planets formed and evolved, and is helping determine how elements needed for life first formed.

11. **STIS**
The Space Telescope Imaging Spectrograph was repaired on orbit by astronauts during SM4. Its main function is spectroscopy—the separation of light into its component colors (or wavelengths) to reveal information about an object’s chemical content, temperature, density, and motion. STIS also performs imaging, covering most of the ultraviolet bands, the entire optical wavelength band, and some wavelengths extending into the near-infrared.

12. **FGS**
Hubble has three Fine Guidance Sensors. Two are needed to point and lock the telescope on the target and the third can be used for stellar position measurements, known as astrometry. During SM4, spacewalking astronauts exchanged one of these optical sensors with a refurbished unit that has enhanced, on-orbit alignment capability.
Observatory Design

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

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

Hubble is big. Excluding its aperture door and solar arrays, the spacecraft is 43.5 feet long—about as high as a four-story building—and 14 feet in diameter at its widest point. Altogether, it would weigh approximately 25,000 pounds on the ground, although it weighs nothing in orbit. About the size of a large school bus, it filled the payload bay of the Space Shuttle Discovery when carried to orbit in April 1990.
Four large, flexible solar-array panels that rolled up like window shades originally provided power to the observatory. Seen below on a water table during a prelaunch deployment test, this original design was replaced in Servicing Mission 3B by rigid panels that are less susceptible to twisting due to the extreme temperature variations they experience in orbit. Although 45 percent smaller than their predecessors, they produce 25 percent more power and reduce the amount of atmospheric drag on the spacecraft. Left: Astronauts Richard Linnehan (partially visible on the end of Columbia’s robotic arm) and John Grunsfeld (center frame) work to install a new, rigid array.
The heart of *Hubble* is its 7.8-foot (2.4-meter) primary mirror, which collects approximately 40,000 times as much light as the human eye. The telescope’s optical layout is known as a Ritchie-Chrétien Cassegrain design. Incoming light bounces off the primary mirror, up to a secondary mirror, and back through a hole in the primary mirror, where it comes to a focal plane that is shared among the suite of scientific instruments. A series of baffles painted flat black and mounted within the telescope suppress stray or scattered light from the Sun, Moon, or Earth.

*Hubble’s* optical system is held together by a supporting “skeleton,” a truss measuring 17.5 feet in length and 9.6 feet in diameter. The 252-pound truss is a stiff, strong, lightweight graphite-epoxy material that resists expanding and contracting in the extreme temperatures of space. A similar material is used in the production of golf clubs, tennis racquets, and bicycles.

The narrow top section of the *Hubble’s* tube-shaped body, known as the forward shell, houses the telescope’s optical assembly. Most of the control electronics for the observatory sit in bays placed around the middle of the telescope, known as the Support Systems Module (SSM), where the spacecraft body widens.

---

*Seen disassembled (above right) for illustration, each of Hubble’s gyroscopes measures the spacecraft’s rate of motion about a particular axis—information that is forwarded to the spacecraft’s pointing control system. The gyroscopic action of the devices is achieved by a wheel inside each gyro that spins at a constant rate of 19,200 rpm on gas bearings. This wheel is mounted in a sealed cylinder that floats in a thick fluid. Electricity is carried to the motor by thin wires, each approximately the size of a human hair, that are immersed in the fluid. Electronics within the gyro detect very small movements of the axis of the wheel. The gyros are packed in pairs inside boxes called rate sensor units (right).*
This middle section is near the telescope’s center of gravity and hence home to the telescope’s four 100-pound reaction wheels—the spinning flywheels *Hubble* uses to reorient itself. Astronauts can easily access the devices within the SSM, and a number of these have been replaced or upgraded during servicing missions.

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

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

Despite these wide thermal swings, the interior of the telescope is maintained by the thermal control system to a narrow temperature range—in many areas to a “comfortable room temperature.” Temperature sensors, electric heaters, radiators, insulation, and thermal paints all work in concert to minimize the expansion and contraction that could alter the telescope’s focus and keep the electronic devices inside the spacecraft at their proper operating temperatures. On the last three servicing missions, astronauts replaced sections of *Hubble’s* external insulation that had broken down from exposure to the harsh conditions of space, adding panels called New Outer Blanket Layers over portions of the spacecraft.

*Hubble* nominally operates via stored commands, computer-based instructions that have associated execution times. The Flight Operations Team (FOT) at NASA’s Goddard Space Flight Center in Greenbelt, Maryland, typically send up a day’s worth of commands at once, although they can also command the spacecraft in real-time during emergencies, engineering tests, or other such scenarios. These commands are uplinked to the spacecraft—and its scientific and engineering data returned to the ground—via a system of NASA geosynchronous communications satellites called the Tracking and Data
Hubble’s instruments collectively observe wavelengths (measured in nanometers) from ultraviolet through infrared. Each instrument was designed to operate in a particular wavelength range and function as an imaging camera or a spectrometer, though some instruments do both. The Fine Guidance Sensors (FGS) not only help the telescope stay locked on target, but can be used as science instruments to accurately determine the relative position of stars.

Relay Satellite System. With the end of astronaut servicing to Hubble, the FOT is transitioning from around-the-clock support to an autonomous operations mode. This should permit continuous operation of the satellite with only a single staffed shift beginning in mid-2011.

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

Batteries are used to allow the telescope to operate while in Earth’s shadow—approximately 36 minutes out of each 97-minute orbit. When fully charged, Hubble’s six nickel-hydrogen batteries contain enough energy to sustain the telescope in normal science operations mode for 7.5 hours, or five orbits. This is approximately the same amount of charge as carried by twelve typical car batteries.

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

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

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

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

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

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

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

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

**Awarding Telescope Time**

The process of observing with *Hubble* begins with an annual call for proposals issued by the Institute to the astronomical community via the web. Astronomers worldwide are given approximately two months to submit a phase one proposal that makes a scientific case for using the telescope. They typically request the amount of telescope time they desire in orbits, each 96 minutes long. Longer observations require a more compelling justification since only a limited number of orbits...
are available. Winning proposals must be well reasoned and address a significant astronomical question or issue. Potential users must also show that they can only accomplish their observations with Hubble’s unique capabilities and cannot achieve similar results with a ground-based observatory.

The primary and secondary mirrors of Hubble form an image in the focal plane of the telescope whose light is shared by the instruments and fine guidance sensors (FGS). Seen here are the locations of the instrument fields of view within the focal plane. In the background is a scale image of the Helix Nebula. Two stars found among the three FGS fields of view are selected as guide stars for the observation.
within a particular astronomical category. Sample categories include stellar populations, solar system objects, and cosmology. The committee organizers take care to safeguard the process from conflicts of interest, as many of the panel members are likely to have submitted their own proposals.

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

The year 2010 had one of the highest subscription rates in the telescope’s history. The astronomical community submitted 1,051 proposals to use the suite of powerful instruments operating on Hubble following Servicing Mission 4. Astronomers requested approximately nine times more orbits than available and submitted six times more proposals than approved.

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

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

Up to 10 percent of Hubble’s time is reserved as discretionary time and is allocated by the Institute director. Astronomers can apply to use these orbits any time during the course of the year. Discretionary time is typically awarded for the study of unpredictable phenomena such as new supernovas or the appearance of a new comet. Historically, directors have allocated large percentages of this time to special programs that are too big to be approved for any one astronomy team. For example, the observation of the Hubble Deep Field (1996) and Hubble Ultra Deep Field (2004)—astronomers’ farthest views to date into the visible-light universe—both used director’s discretionary time.
The Institute creates a long-range schedule to order the diverse collection of observations awarded telescope time as efficiently as possible. This task is complicated because the telescope cannot be pointed too close to bright objects like the sunlit side of Earth, the Sun, and the Moon. Adding to the difficulty, each astronomical target can only be seen during certain months of the year; some instruments cannot operate in the high space-radiation areas of Hubble’s orbit; and the instruments regularly need to be calibrated. Preparing for an observation also involves selecting guide stars to stabilize the telescope’s pointing and center the target in the instrument’s field of view. The selection is done automatically by the Institute’s computers, which choose two stars per pointing from a catalog of almost a billion stars.

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

At Goddard, a number of groups conduct mission operations for the observatory. A flight operations team (FOT), along with a group of spacecraft engineers, maintain the health and safety of the observatory. Together, they monitor Hubble’s telemetry and check the spacecraft’s subsystems for correct daily performance and longer-term trends.
Other personnel are responsible for modifying Hubble's flight software. Extensive software testing facilities and simulators assure that any changes to this code are done safely. Programmers, system administrators, hardware field engineers, database administrators, and testers all coordinate activities at Goddard to keep the mission operations systems functioning reliably. Similar groups at the Institute ensure the integrity of the science operations systems.

Communication with Hubble is accomplished via NASA's Tracking and Data Relay Satellite System (TDRSS). The TDRSS's satellites provide nearly continuous communications coverage with Hubble. FOT members uplink the command load files from the Institute into Hubble's main onboard computer, which then executes the commands at prescribed times to maneuver the telescope and take observations. Solid-state data recorders store the science data on the spacecraft. FOT members have the responsibility of managing the content of these recorders and periodically transmitting the data to TDRSS's ground terminal at White Sands, New Mexico. From there, the data is sent to Goddard to ensure its completeness and accuracy. Goddard then sends the data to the Institute for processing, calibration, and archiving.

Currently the Space Telescope Operations Control Center at Goddard is staffed by the FOT around the clock, but efforts are underway to automate routine commanding and move to a single staffed shift. When this change occurs, computer systems will monitor telemetry from the spacecraft during the unstaffed shifts and alert appropriate personnel via a paging system when anomalies occur.

Hubble generates approximately 600 gigabytes of science data each month. Astronomers typically download 3 to 5 terabytes of data from the archive every month. By the end of 2010, this data had been used to publish more than 9,400 peer-reviewed scientific papers.

One Astronomer's Story

One of the most interesting observations of 2010—the investigation of a strange-looking object in the asteroid belt—employed director's discretionary time. On January 6, 2010, an object named P/2010 A2 was discovered by a ground-based telescope. It was listed as a periodic comet because it had a tail-like feature unique to comets and a relatively short orbital period around the Sun. Although it had the physical appearance of a comet, it was orbiting within the solar system's asteroid belt, something very rare for comets.

California astronomer Dr. David Jewitt immediately became interested in this object and arranged to examine it with the WIYN telescope at Kitt Peak, Arizona. He discovered that its appearance was not that of a regular comet. A regular comet
Jewitt wondered if this object was actually an impact between two asteroids—something that had never before been seen. He quickly applied for discretionary time on Hubble to view the object with better clarity than ground-based telescopes could provide. He hoped to find additional evidence that the main body was a recently impacted asteroid or to somehow disprove the idea.

Jewitt applied for six orbits. Experts drawn from the most recent time allocation committee reviewed the proposal. Based on their reviews, the committee members awarded three orbits. On January 25, 2010, Hubble took its first images of P/2010 A2. They showed a nucleus leading a trail of dusty debris, but unlike a classical comet, the edges of this trail were basically parallel to each other instead of being more fan-shaped. Even more noteworthy, Hubble revealed that the head of this trail of debris was a complicated X-shaped, filamentary structure—an unprecedented sight for Hubble or any other other telescope.

The observations confirmed Jewitt’s suspicion that this was a highly unusual object. Based on these initial findings, he and his collaborators wrote a second proposal for six more orbits of discretionary time to monitor the appearance of this object over the next few months. The Institute director accepted the proposal in full, and these observations were scheduled...
uniformly so Jewitt and his team could systematically watch the appearance of P/2010 A2 evolve. Dr. Jewitt has also been awarded an additional five orbits to view the object in the summer of 2011.

This series of observations demonstrates the importance of maintaining discretionary time within the overall strategy of scheduling *Hubble*. It is impossible for standard general observer proposals to anticipate the many transitory events that occur in the universe. Discretionary time allows *Hubble* to capitalize on discoveries made elsewhere, such as P/2010 A2, and bring further insight to them with the resolution that only *Hubble* can currently provide.

*Left:* Originally believed to be a comet, this ground-based image of P/2010 A2 was used to identify the astronomical body as an “object of interest.” (Photo credit: James Annis/Fermilab, Marcelle Soares-Santos/Fermilab and University of Sao Paulo, and David Jewitt/UCLA)

*Right:* The *Hubble* observations revealed that the object was an asteroid (the white object on the left side of the image) with a debris trail that resulted from a collision with a second asteroid.
This 20th anniversary Hubble photo release typifies the remarkable imagery produced by the orbiting observatory for two decades. It shows a three-light-year-long pillar of gas and dust in the Carina Nebula. Scorching radiation and streams of charged particles from hot newborn stars in the nebula are shaping and compressing the pillar. This stellar nursery is located 7,500 light-years away in the constellation Carina.
Twenty Years with *Hubble*

The universe looked different in 1990. At that time, the most powerful optical telescopes could only see about halfway across its estimated extent. Calculations of its age disagreed by large margins. Scientists only theorized that colossal black holes were the powerhouses behind a range of energetic phenomena seen in galaxies. Astronomers weren’t sure if planets orbited other stars.

The astronomical landscape changed dramatically with the launch of the *Hubble Space Telescope* into Earth orbit in April 1990. Later joined by its sister observatories, NASA’s *Spitzer Space Telescope* and *Chandra X-ray Observatory*, *Hubble* became a trailblazer in the new age of astronomical discovery.

Compared with the giant 10-meter mirrors found at mountaintop observatories today, *Hubble*’s 2.4-meter diameter seems small. Situated above Earth’s atmosphere, however, the telescope consistently produces sharper images across a wider field than ground-based telescopes. It also needs no adaptive optics—mirrors that adjust many times a second to compensate for the constantly changing atmospheric conditions which make stars appear to twinkle as seen from the ground.

From its vantage point in space, *Hubble* has the unique ability to see very faint objects because there is no glowing sky background. Without Earth’s atmosphere to block certain wavelengths of light, *Hubble* can also see clearly across a wide swath of the spectrum, from ultraviolet to near-infrared, giving it truly “panchromatic” vision. With no weather to interfere, its optically consistent view permits the telescope to revisit targets with the sure expectation of gathering data at the same sensitivity and of the same quality.

Armed with these powerful capabilities, *Hubble* has enabled remarkable discoveries across the increasingly broad field of astronomy. Its users have written more than 9,400 peer-reviewed papers during the past two decades—science that is causing astronomy textbooks to be rewritten. The telescope’s regular, astounding images have reinvigorated the public’s interest in the wonders of the universe. Millions of hits recorded each month on the project’s public image servers attest to this interest.

---

*One of the many ways Hubble has revolutionized modern astronomy is through its study of planetary nebulas. Observations of the Cat’s Eye Nebula (NGC 6543), for example, revealed more intricate structures produced by gas shells, shockwaves, and stellar jets than ever imagined.*
Galaxy Evolution

In 1990, astronomers could detect galaxies only to a distance of 7 billion light-years where they found fully developed spiral and elliptical galaxies. Scientists hypothesized that these galaxies must have evolved from earlier forms, but if these objects existed, they could not be seen. There were years of conjecture and theoretical modeling about how and when galaxies arose if the universe was once a cooling fireball from the Big Bang. Ground-based observations were unable to establish which of several competing theories best described reality.

In 1985, five years before its launch, a committee of top astronomers discussing Hubble concluded that devoting a large amount of time to a “deep exposure” of the universe would be fruitless. Extrapolating from the known universe of the time, they assumed that the geometry of space at great distances would disperse the light of normal galaxies, making them too diffuse to be seen—even by Hubble.

To everyone’s surprise, Hubble observations showed galaxies at a record-breaking distance of more than 9 billion light-years. The galaxies appeared more compact than expected. With their dim light concentrated into a smaller area, they were easier to detect. The universe also looked somewhat disorganized at these greater distances. Astronomers noted many strangely shaped galaxies, and even normal galaxies contained knots of star birth that were unusually bright.

These findings encouraged astronomers to conduct the deep exposure they had previously thought fruitless. In December 1995, a historic eleven-day-long observation called the Hubble Deep Field image was released in 1996, it was the farthest visible view of the universe ever captured. The image covers a portion of sky 1/30th the diameter of the full Moon. Though the field is very small, it is thought to represent the typical distribution of galaxies in space. In this image, Hubble uncovered at least 1,500 galaxies at various stages of development.
*Hubble* Deep Field captured light from a tiny area of sky near the Big Dipper. As a result, astronomers saw faint galaxies out to the remarkable new distance of 12.2 billion light-years. The faintest galaxies detected were approximately half a billion times fainter than the faintest objects that can be seen with the unaided eye.

When *Hubble*’s more sensitive Advanced Camera for Surveys was installed in 2002, another long exposure was conducted. Called the *Hubble* Ultra Deep Field, this observation detected light 2.5 times fainter than the first exposure and found fragmentary, developing galaxies approximately 13.1 billion light-years away.

Observations from 2009 to 2010 with the even more sensitive Wide Field Camera 3 (WFC3), which was installed in 2009 during Servicing Mission 4, pushed deeper still. WFC3 identified at least one early galaxy 13.2 billion light-years distant—at the practical limit of *Hubble*’s sensitivity. Astronomers think this light originated when the universe was only 500 million years old. *Hubble*’s planned successor, the *James Webb Space Telescope*, is needed to probe beyond this point.

Like individual frames of a motion picture, the *Hubble* deep field surveys have captured and revealed a timeline for the emergence of structure in the early universe as well as the ensuing stages of galaxy evolution. Before *Hubble*, nearby colliding galaxies were simply curiosities. Now the deep *Hubble* surveys show that galaxy interactions were more the rule than the exception in the early days of the universe. This provides direct and compelling, visual evidence that the universe is changing as it ages.

---

This detail shows approximately one quarter of the entire *Hubble* Deep Field image. It reveals that besides well-formed spiral and elliptically shaped galaxies, there are many objects with irregular sizes and shapes. These latter objects provide important clues for understanding the evolution of galaxies.
Released in 2004, the Hubble Ultra Deep Field image presented a small but extremely sensitive core sample of the universe. Taken by the Advanced Camera for Surveys, the exposure integrated light from across billions of light-years and captured approximately 10,000 galaxies of various ages, sizes, shapes, and colors. The smallest, reddest, and most unusually shaped galaxies are the most distant. The larger, brighter, well-defined spiral and elliptical galaxies are closer to our Milky Way galaxy.
Supermassive Black Holes

A black hole is an invisible region in space marking the location of an object whose gravitational attraction is so strong that essentially nothing, not even light, can escape it. The material inside a black hole is concentrated into a single point of infinitely high density that distorts space and time. When Hubble was launched, black holes were only known to exist in certain binary star systems. Made unstable by siphoning material from its stellar neighbor, the accreting star in such a system explodes and its remaining core collapses into a black hole. The mass of the black hole produced is a few times that of our Sun.

Astronomers suspected, however, that far more massive black holes must be the “gravitational engines” powering a wide range of other extraordinary phenomena observed. These marvels included galaxies with extragalactic jets and powerful radio emissions, and quasars, the intensely bright, star-like objects appearing at galactic distances.

Arp 148 is the spectacular aftermath of an encounter between two galaxies, resulting in a ring-shaped galaxy and a long-tailed companion. The collision produced a shockwave effect that first drew matter into the center and then caused it to propagate outward in a ring. Hubble observations show that galaxy interactions such as this were more common in the early universe.
First discovered in the 1960s using ground-based telescopes, these quasars, or quasi-stellar objects, could be seen at distances of approximately 10 billion light-years. Their true nature remained mysterious, however, as the quasars' host galaxies could not be seen. Astronomers only knew that quasars were more abundant in the distant past. *Hubble* observations in 1996 confirmed that quasars reside in the cores of a remarkable variety of galaxies, many of which are colliding.

Soon after astronauts installed the Space Telescope Imaging Spectrograph (STIS) in 1997, astronomers aimed it at the nearest mini-quasar, the brilliant heart of the giant elliptical galaxy M87 in Virgo. There, *Hubble* measured a mass three billion times that of our Sun. STIS accomplished this by making velocity measurements of a previously unseen spiral-shaped whirlpool of hot gas orbiting the galaxy's center. The disk's velocity indicated the presence of a very high concentration of mass at the galaxy's core—vastly exceeding what stars alone could produce but completely consistent with that of an exceedingly massive black hole.

A 1997 census of 27 nearby galaxies found that they all had supermassive black holes at their centers. This led astronomers to conclude that supermassive black holes are so common that every major galaxy has one. Additionally, *Hubble* observations...
revealed a relationship between the mass of a central black hole and the mass of its galaxy's central bulge of stars: the bigger its bulge, the more massive its black hole. This links galaxy evolution to the growth of black holes through some yet unknown feedback mechanism.

Astronomers continue to search for the cause of this relationship.

**Dark Energy**

Before *Hubble*, most scientists thought that the material in the universe must be exerting some degree of gravitational drag on the expansion of space after the Big Bang—something like the slowing effect of gravity on a ball tossed into the air.

For decades, however, scientists questioned whether the force exerted by this gravitational draw would be able to halt the expansion of the universe completely.
To answer the question, scientists needed to determine the expansion rate history of the universe. This required a telescope that could see far enough to provide data from the earliest epochs. A major scientific justification for building Hubble was to settle this important debate by actually measuring the deceleration rate.

Determining distances accurately is key to ascertaining this expansion rate history. At the very greatest distances, astronomers can only see the very brightest objects. One such object is an exploding star, or supernova. Several types of these have been identified. They are distinguishable from one another by their brightness and duration of visibility. One particular kind of supernova, known as Type Ia, explodes with a reliably consistent intrinsic brightness. Astronomers call them “standard candles” because, like candle flames, they produce a predictable quantity of light when ignited. Since this characteristic brightness is known, and because its apparent brightness dims predictably with distance, scientists can calculate the distance to the supernova by measuring its apparent brightness.

In 1998, Maryland astronomer Adam Riess wrote a computer program to calculate the universe’s deceleration rate from Type Ia supernovas are so bright they can be seen at great distances. This allows astronomers to trace the expansion rate of the universe and to determine how it is affected by the repulsive push of dark energy, a mysterious form of energy that pervades space.
If the repulsion from dark energy grows stronger than the current measurements, the universe may be torn apart by a future “Big Rip,” during which the universe expands so violently that everything from galaxies to atoms comes undone. At the other extreme, dark energy may become an attractive force, possibly leading to a “Big Crunch,” where the universe ultimately implodes.

THE “BIG RIP”
Strengthening dark energy speeds up the universe, causing it to break apart.

CONSTANT EXPANSION
The universe expands more gradually, in balance with gravity.

THE “BIG CRUNCH”
As dark energy weakens, gravity causes the universe to collapse.

Many precise observations of supernovas are needed to determine which path the universe will take.
Type Ia supernova data collected by his team. To his surprise, the program continually derived a negative value for the mass of the universe. Riess at first thought this was simply a programming error, but he then realized that the program was trying to make sense out of the nonsensical. The data showed that instead of expanding and slowing, the universe was expanding and accelerating.

At the same time, in California, a team led by Saul Perlmutter independently discovered a similar acceleration in their data. Like Riess, his team found that distant supernovas were dimmer than predicted. This meant that the Earth was farther from them than expected if the universe was slowing down or even just “coasting.” They too concluded that the universe must now be expanding at a faster rate than earlier in its history.

Both groups had discovered a previously unknown characteristic of the universe: something is causing it to expand more quickly over time. Because of its unknown origin, it is simply called “dark energy.” Albert Einstein’s mathematical equations for the universe include a repulsive element which he called the cosmological constant. Astronomers don’t yet know whether the observed phenomenon behaves precisely as Einstein’s constant predicts mathematically.

The nature of dark energy was somewhat illuminated by later Hubble observations of a supernova approximately 10 billion light-years distant. This one was measured to be anomalously bright! The observation, along with others, indicated that the universe was indeed decelerating as expected very long ago, but has sped up between then and now. The transition period between its slowing and accelerating apparently occurred about 5 billion years ago.

Research on the magnitude and nature of dark energy has now become a top priority for 21st-century astrophysicists. Many additional hours of Hubble telescope time are already scheduled to gather further data in this exciting field of investigation.

**Measuring the Galaxy Distance–Speed Relationship**

In the early part of the 20th century, astrophotography and spectroscopy were relatively young technologies. With the instrumentation of the time, it was very difficult to determine the nature, distances, and motions of the nebulous objects observed in the night sky. Scientists and philosophers alike were seeking to process logically what they saw in nature. Both tried to understand where Earth and the solar system “fit” within the universe and how long they had existed. Judging from the available evidence, Einstein himself concluded the universe must be static and perhaps therefore eternal. Otherwise, according to his theory of general relativity, it would have flown apart or collapsed.
In 1929, Edwin Hubble provided the first strong observational evidence that the universe had a finite age. Using the spectroscopic redshift of galactic light, he demonstrated that the farther an observed galaxy was from Earth, the faster it appeared to race away. This linear relationship of the outward speed of galaxies to their distances from Earth, now called the Hubble Constant ($H_0$), meant space was expanding uniformly in all directions. In fact, the reddening of distant galactic light is not caused by true space velocity—as it would be if caused by the Doppler effect (see sidebar on page 123)—but rather the expansion of space itself stretching light to longer wavelengths.

By determining the current extent of the universe and its expansion rate, the cosmic chronometer could be reversed and the age of the universe calculated. But this age could only be as accurate as the uncertainties in the galaxies’ distance measurements. Thus, an early, key project for Hubble was to determine the most accurate value possible for the Hubble Constant by refining the distances to galaxies. Hubble was uniquely suited for the task because it alone had sufficient acuity to resolve individual stars in other nearby galaxies, a key element in the technique planned.

To make the improved distance measurements, astronomers had to find stars in galaxies of a particular type called Cepheid variables. These stars cycle rhythmically in brightness over a period of days to weeks. Like Type Ia supernovas, Cepheid
variables can be used for measuring distances. This is because the amount of time it takes for a Cepheid to go through its full cycle of brightening and dimming is directly related to its intrinsic brightness: the longer the cycle, the brighter the star. Once astronomers could measure this rate and establish its intrinsic brightness, they could compare this value to the star’s apparent brightness and the distance to the Cepheid calculated.

When Hubble was launched in 1990, the value of $H_0$ was estimated to range over a factor of two from 50 to 100 kilometers per second per megaparsec. (A megaparsec equals 3.3 million light-years). When used to calculate age, these values implied that the universe could be anywhere from 8 to 16 billion years old.

In 1994, California astronomer Wendy Freedman—leader of the Hubble Space Telescope Key Project on the Extragalactic Distance Scale—announced a value of 80 kilometers per second per megaparsec, with a $\pm 17$ margin of error. The results were perplexing because they suggested a universe only 8 billion to 12 billion years old, which was younger than the accepted age of its oldest stars. If true, it implied that well-vetted computer models of stellar evolution were inaccurate.

By the late 1990s, scientists continued to refine the value of the Hubble constant, leading to an uncertainty of only about ten percent. In 2009, Adam Riess and his collaborators further streamlined and strengthened the construction of a cosmic “distance ladder” by observing Cepheids in the distant galaxy NGC 4258. They measured the expansion rate at 74.3 kilometers per second per megaparsec, narrowing its uncertainty to no more than five percent.

In hindsight, Riess’s value simply split the difference between the earlier 50 to 100 kilometer per second per megaparsec values. This newly derived value yields an age of 13.7 billion years for the universe—old enough to accommodate the measured ages of the oldest stars.

With additional careful measurements astronomers believe they can continue to narrow the uncertainty in $H_0$. Their new goal is to ascertain this value to within one percent.
On February 23, 1987, a stellar explosion occurred in the Milky Way’s small neighboring galaxy known as the Large Magellanic Cloud (LMC). This image shows the supernova’s remnant as it appeared approximately a decade later (see the multi-ringed object slightly to the left and above center). The LMC is located within the southern constellation of Dorado, the fish.
Stellar Evolution

Stars are the basic building blocks of galaxies. Their ongoing evolution drives a “galactic ecology” where the hydrogen and helium from the Big Bang are reprocessed into heavier elements through nuclear fusion. These elements are then recycled into second- and third-generation stars. The fundamental physics of stars and the process of nucleosynthesis—the creation of heavier elements from lighter ones—have been worked out by theorists over the past century. However, confirming these theories through actual observations has been difficult because of the high sensitivity and resolution required. Hubble has contributed greatly to this enterprise, revealing many previously unseen details in the life cycles of stars. Some of these contributions, described below, include stars with gas jets, nebulas, and supernovas.

A new star announces its birth to a galaxy by ejecting a pair of gaseous jets that form remarkable spindle-shaped structures deep inside its star-forming cloud. Named after George Herbig and Guillermo Haro, who studied these objects in detail in the 1940s, these Herbig-Haro jets plow into the interstellar medium at supersonic speeds. Over 15 years, Hubble images have been assembled into movies showing the outflow of these jets. The movies reveal how the jets wobble, much like the axis of a child's top, tracing out a cone shape emanating from the star. This precession is due to the action of the young star itself or its circumstellar disk of gas that is feeding material onto the star.
More than two centuries ago, the philosopher Immanuel Kant proposed that the solar system planets were born out of a circumstellar disk surrounding the newborn Sun. He regarded the orbits of the planets, roughly in the same plane with one another, as a skeleton of such a disk. Hubble has been able to uncover other such disks buried deep inside the Orion Nebula, a nearby star-forming region. The black disks, seen in silhouette against the glowing hydrogen walls of the nebula, are considered embryonic planetary systems. Subsequent Hubble pictures revealed that these disks exist in other star-forming regions as well.

Stars like our Sun go through a rapid series of changes late in their lives as the rate of thermonuclear fusion readjusts to the star's changing supply of internal fuel. The consequences are that late in a star's life, the heated outer shells of gas escape into space to form largely spherical-looking planetary nebulas. Prior to Hubble, astronomers thought they had a fairly complete picture of this late stage of stellar evolution. But Hubble surveys of nearby planetary nebulas have revealed much more complex structures than previously imagined. Some nebulas are distinctly bipolar, meaning the outflow of material is probably constricted by a circumstellar disk around its center. Others are mysteriously point-symmetric, having complex but not uniform patterns mirrored on either side of the dying star. Still other nebulas superficially look like smoke rings but are actually tubes of gas pointed in our direction.

This image, released 20 years after the star's explosion, shows the entire region around Supernova 1987A. The striking, light-year-wide ring was probably shed by the star around 20,000 years ago. Supernova 1987A is 168,000 light-years away in the Large Magellanic Cloud.
Long suspected by astronomers to be an early stage of planetary formation, protoplanetary disks are seen around infant stars in these Hubble images taken during a survey of the Orion Nebula. The red glow in the center of each disk is a young, newly formed star. Over time, the disks may develop into planetary systems like our Sun's.
Supernovas play a critical role in stellar evolution as well. In 1987, the nearest supernova within the past 400 years occurred 168,000 light-years away in a small neighboring galaxy called the Large Magellanic Cloud. *Hubble* has provided a closer look into its stellar dynamics. Although launched three years after the explosion, astronomers pointed *Hubble* toward the star shortly thereafter. The telescope clearly showed a glowing ring of gas more than one light-year wide encircling the expanding supernova remnant.

Subsequent exposures following *Hubble*’s optical repair in 1993 revealed two outer rings that are likely the edge of an hourglass-shaped stellar outflow that preceded the explosion. Over the past 16 years, scientists have used *Hubble* to track changes in the rapidly evolving structure. The shockwave from the supernova began to hit the inner ring in the late 1990s. Bright knots of gas have been observed to light up sequentially as the shock progresses through the ring. Never before have astronomers been able to follow such changes in the aftermath of a supernova.

*Hubble* will certainly continue to study this propitiously timed supernova in the years to come.

**Solar System Science**

*Hubble*’s resolution is unmatched by ground-based observatories, so it leads the field in gleaning details from targets so distant that they appear motionless on the sky. The telescope was also designed to observe moving targets, however, and so has punctuated the last two decades with textbook-changing solar system observations. Noted here are some of the more important ones.
By 1990, all the major planets in the solar system had been examined up close by interplanetary spacecraft. Just a year before Hubble’s launch, the Voyager 2 space probe visited the outermost major planet Neptune, three years after imaging Uranus. Voyager 2’s snapshots offered only brief, single-season looks at these planets. Follow-up observations by Hubble revealed that both planets possess atmospheres that show dramatic seasonal variations.

In 1992, Hubble discovered that the large southern hemisphere dark spot seen on Neptune by Voyager 2 in 1989 had mysteriously disappeared. To compound the mystery, Hubble later photographed a different dark storm emerging in Neptune’s northern hemisphere.

When Voyager 2 passed by Uranus in 1986, the planet was in northern summer and appeared bland and featureless. Because the ice giant is tilted on its side, one pole of the planet was covered in darkness. But in the ensuing years, as Uranus slowly moved toward its equinox in 2007, Hubble followed the seasonal stirring of the planet’s atmosphere by imaging circular storms upon the once-bland object. Hubble was also the first telescope to photograph the planet’s ring system and, in fact, discovered additional rings while doing so.

After the first servicing mission in 1993 that corrected Hubble’s focus, the telescope was quickly made ready to observe the unprecedented impact of Comet Shoemaker-Levy 9 (SL9) into the planet Jupiter. The comet had been ripped apart into at least two-dozen fragments by Jupiter’s gravitational tidal force. Over a 10-day period in July 1994, Hubble meticulously recorded the aftermath of each piece falling into Jupiter’s atmosphere and exploding. Without Hubble’s resolution, astronomers would not have learned how the pieces of cometary debris were dispersed by winds in Jupiter’s atmosphere.

Only 15 years later, Hubble caught the appearance of yet another dark spot in Jupiter’s atmosphere. The detailed analysis done on the earlier SL9 data allowed astronomers to conclude quickly that in this case a single minor body had collided with the planet. Analysis of the plume indicated that an asteroid had hit Jupiter, not a comet. A year later, amateur astronomers noted a bright flash of light on Jupiter and Hubble was used to scan the area for evidence of an impact. This time, the absence of a sooty cloud meant that the impacting body had disintegrated above the cloud tops as a fireball.

Hubble has also proven invaluable to planetary scientists through its regular monitoring of Jupiter’s dynamic atmosphere. In May 2006, observations of a new red spot made headlines. It emerged over a period of many months from the collision and consolidation of a series of smaller spots. The new spot is about half the size of Jupiter’s Great Red Spot. Why either spot is colored red remains a mystery.
Saturn and Mars

Farther out in the solar system, the beautiful planet Saturn has been the target of a coordinated observing campaign between *Hubble* and NASA’s *Cassini* spacecraft, currently orbiting the planet. Of interest have been the puzzling Saturn auroras. Once simply thought to mimic characteristics seen in Earth’s and Jupiter’s auroras, simultaneous observations by *Hubble* in ultraviolet wavelengths and by *Cassini* of radio emissions have shown otherwise. Saturn’s polar lights are fundamentally different from both of its sister planets. Saturn’s auroral displays become brighter on the sector of the planet where night turns to day as the magnetic storms increase in intensity. This behavior is not seen in Earth’s or Jupiter’s auroras. At certain times, Saturn’s auroral ring has also appeared more like a spiral than a ring. Finally, the pressure of the solar wind has a much larger role overall on Saturn’s upper atmosphere than previously thought.

Moving inward, understanding the weather on the planet Mars is critical to planning future robotic probes and eventually a human mission there. Although numerous artificial satellites are closely orbiting and photographing Mars presently, *Hubble* can monitor the entire planet in significant detail with one simultaneous view. This was invaluable in the summer of 2003, when *Hubble* traced the emergence of a dust storm in the Red Planet’s Hellas basin that engulfed the entire planet in just a few days.

Dwarf Planets and Asteroids

Scientists have also used *Hubble* to assist the upcoming probes of dwarf planets and asteroids by other missions. In 2015, NASA’s *New Horizons* spacecraft is scheduled to visit Pluto, the best-known dwarf planet. In preparation for this rendezvous, *Hubble* was used to gather details on the tiny surface variations first seen on Pluto by ground-based telescopes. *Hubble*’s observations revealed surface features that are only a few hundred miles across. This is remarkable given the distance to Pluto is approximately 3 billion miles.

Photos of the dwarf planet revealed a variegated world with white, dark orange, and charcoal black terrain. Comparing *Hubble* pictures taken in 1994 with those taken in 2002 and 2003, astronomers found evidence that the northern polar region brightened, while the southern hemisphere became darker. These changes hint at complex seasonal processes affecting the visible surface. *Hubble*’s superior image resolution allows planetary astronomers to better interpret the Pluto observations from other telescopes taken over the last three to four decades.
This Hubble image of the planet Jupiter reveals the impact sites of two fragments from Comet Shoemaker-Levy 9. Twenty-one large chunks of the comet rained down upon Jupiter in July 1994. The impact sites, located in the planet's southern hemisphere, are the dark spots in the lower left of the planet.

In July 2009, 15 years after Comet Shoemaker-Levy 9 slammed into Jupiter, the planet was hit by an asteroid. This Hubble picture is the sharpest visible-light image taken of the impact feature.
In 2005, *Hubble* made news by discovering two small, previously unknown moons of Pluto. A year later the International Astronomical Union named them Nix and Hydra. In Greek mythology, Nix is the goddess of the night. One of her offspring is Charon, the name of Pluto’s largest moon. The mythological Hydra was a nine-headed serpent with poisonous blood that had its den at the entrance to the Underworld. The names of these two figures were chosen because their first letters, *N* and *H*, also honor NASA’s New Horizons spacecraft and *Hubble*.

In a similar support role, *Hubble* observations of the asteroid Vesta—a target for the *Dawn* spacecraft in July 2011—have revealed its axis of rotation is tilted approximately four degrees more than scientists previously thought. This means the change of seasons between the southern and northern hemispheres of Vesta may take place about a month later than expected. Armed with this important knowledge, mission planners for *Dawn* plan to adjust the spacecraft’s orbit for maximum solar illumination when it begins imaging and mapping activities.

*Hubble*’s observations of the dwarf planet Ceres—a later destination for the *Dawn* spacecraft in 2015—were so precise that astronomers could measure its shape. It is nearly round, suggesting the body has a rocky inner core and a thin, dusty outer crust. The slight oblateness of the object suggests it has a mantle of liquid water.
In January 2010, astronomers were mystified to see a comet-like object with a tail suddenly appear in the asteroid belt. *Hubble* observations revealed a strange X-shaped pattern at the head of the comet-like tail. It is now thought that two asteroids collided and left a trail of dust—the first time such an event has been documented. Without the resolution that *Hubble* provides, astronomers might have simply concluded that the object was a water-laden asteroid outgassing like a comet.

The solar system is clearly a dynamic place, and *Hubble* will continue to be used effectively in its study for years to come.

---

Discovered in 1801, Ceres is the largest object in the asteroid belt. It is approximately 590 miles across. Astronomers enhanced the sharpness in these *Hubble* images to better reveal the bright and dark regions, which could be asteroid impact features. Ceres’ round shape suggests that its interior is layered like Earth’s. Ceres may have a rocky inner core, an icy mantle, and a thin, dusty outer crust, inferred from its density and rotation rate of 9 hours.

---

**Extrasolar Planets**

Planets orbiting other stars were not discovered until five years after *Hubble*’s launch. In 1995, ground-based experiments uncovered indirect evidence for planets by noticing tiny wobbles in their velocities through space. Most of the approximately 500 exoplanets found to date have been through this stellar radial velocity technique. In 2000, a powerful new approach was employed. Astronomers using extremely sensitive photometers found they could detect the slight dimming of a star’s light when a planet passes in front of, or *transits*, it. This method additionally provides a rough mass estimate for the exoplanets it discovers.
Planets detected via transit opened the possibility of characterizing their atmospheres by analyzing the changing spectrum of starlight seen before, during, and after their crossing. In 2001, Hubble made the first measurements of the atmosphere of an exoplanet. In a landmark observation, Massachusetts astronomer David Charbonneau spectroscopically measured a parent star's light as it filtered through exoplanet HD 209458b's atmosphere. Somewhat surprisingly, the element sodium was detected.

In subsequent observations, Hubble has found carbon dioxide, methane, oxygen, and water vapor on transiting exoplanets. These particular foreign worlds are located very close to their parent stars and are therefore not conducive to life because of the planets' extremely high temperatures. Nevertheless, astronomers using this technique may be able to detect planetary atmospheres in the future that are similar to Earth's in temperature and composition.

Meanwhile, Hubble made history in 2008 when scientists announced that they had used it to take the first visible-light image of an exoplanet. The feat was accomplished using data taken over the years 2004–2006 of the star Fomalhaut. Uncovered in the data was a giant gas planet in orbit near the inner edge of a large dust ring encircling the star. No larger than three times the size of Jupiter, the planet is unusually bright, perhaps because it is surrounded by a sizable ring of ices and debris similar to the planet Saturn's ring system.

In a field that is rapidly gaining in importance, astronomers will no doubt continue to use Hubble data to identify and characterize exoplanets orbiting other stars.
Impact of *Hubble* on Culture

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

*Hubble* has ushered in a new age of science exploration. Public opinion surveys show that science literacy has risen 10 percentage points since astronauts repaired *Hubble* in 1993. Though this cannot be attributed to *Hubble* exclusively, the accomplishments of the space telescope have certainly contributed to elevating public awareness of scientific research.
Coincident with Hubble’s repair in the early 1990s was the rapid growth of the Internet and high-speed data transmission into households. The immediacy of the Internet made Hubble images easily accessible to a broad range of society. This allowed teachers, parents, and children alike to track the preparation and execution of the Hubble servicing missions and become familiar with the telescope, its instrumentation, and its accomplishments.

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

The Hubble Space Telescope also permeates educational material. If one compares an astronomy textbook from the late 1980s to a textbook published today, the differences are extraordinary. Nearly every chapter of contemporary textbooks contains Hubble pictures that are seminal to the topics at hand: supermassive black holes, stellar evolution, planet impacts, cosmology, and galaxy classification, to name a few. The same is true for online references such as Wikipedia that now are replete with Hubble photos illustrating astronomical discoveries.

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

This popular book, published by the National Geographic Society, is an example of other similar books that document Hubble’s history and remarkable images.
In October 2010, the Istituto Veneto di Scienze, Lettere ed Arti in Venice, Italy featured an exhibition entitled The Hubble Space Telescope: Twenty Years at the Frontier of Science. Displayed in the beautiful and historic Palazzo Loredan, the exhibits included many breathtaking Hubble photos taken over the years, as well as artifacts from the telescope and tools used by astronauts in the missions to repair and upgrade it. (Photo credit: Bob Fosbury, ESA/Hubble.)
The Future

Thanks to the ingenuity of scientists, engineers, and Space Shuttle astronauts, Hubble’s cameras and spectrographs have been upgraded with state-of-the-art instrumentation. Today Hubble is vastly more powerful and efficient than when it was launched in 1990. It should continue operating well into the current decade.

The telescope has a very long list of ambitious observations already scheduled. Three large, multi-year programs, which account for about 25 percent of Hubble’s observing time, are currently underway in parallel with the other approved programs. These specially solicited, Multi-Cycle Treasury Programs are designed to fill the archive with data on galaxy clusters, stellar populations, and cosmology that can be analyzed for years after the telescope ceases to operate. These programs should help astronomers to refine the nature of dark matter and dark energy.

The telescope will also be used to search for target Kuiper belt objects for the New Horizons spacecraft to visit after it flies by Pluto in 2015. This is just one of many other coordinated observations with various ongoing NASA missions that the Hubble observatory will undertake. Though extraordinarily productive during the last two decades, it is very possible that Hubble’s greatest contributions to science may still lie ahead.

Among its many honors, Hubble and its images (clockwise) have been depicted as a Google Doodle, portrayed on U.S. Postage stamps, graced the cover of National Geographic, and featured on NOVA, the most watched documentary series on U.S. Public broadcasting. (*Reproduced by permission of the publisher from National Geographic (April 1997), 2001 by the National Geographic Society. †Reproduced by permission of the publisher from NOVA: Hubble’s Amazing Rescue, 2009 by WGBH Educational Foundation.*)
Queen Elizabeth II and Prince Philip, the Duke of Edinburgh, receive a framed photograph of the Hubble Space Telescope from Maryland's Senator Barbara Mikulski and Representative Steny Hoyer during a visit to the Goddard Space Flight Center in May 2007.
The Making of the Imax *Hubble 3D* Movie

*Hubble* images are brought to three-dimensional life in the spectacular IMAX movie, *Hubble 3D*, which debuted worldwide in March 2010. The movie chronicles the life of the 20-year-old *Hubble* telescope and includes highlights from STS-125, the fifth and final astronaut servicing mission to repair and refurbish the observatory.

Narrated by actor Leonardo DiCaprio, the 43-minute film was designed to give viewers the unique visual perspectives of seeing the universe through *Hubble*, voyaging through the cosmos, and peering over the shoulders of astronauts as they work in space. Its three-dimensionality provides a sense of realism and immediacy beyond the reach of two-dimensional moving images.

Approximately two years before launch, representatives of the IMAX Corporation contacted NASA to propose a partnership that would include flying its specialized camera aboard the Space Shuttle *Atlantis* during STS-125. NASA assembled a team of *Hubble* engineers at the Goddard Space Flight Center to design a custom hardware interface that could carry the camera to orbit mounted in the orbiter’s payload bay. They also assisted the IMAX team in meeting all of the stringent Shuttle and *Hubble* safety requirements for the camera system and passing NASA’s thorough prelaunch tests.

Around the same time, the IMAX Corporation contacted the Space Telescope Science Institute about showcasing three-dimensional versions of some of *Hubble*’s iconic images, as well as those that would be captured by the IMAX camera installed in the Space Shuttle. The Institute team—consisting of astronomers, science...
visualization experts, and image specialists—needed to convert flat, two-dimensional images into a three-dimensional environment which would provide viewers the impression they were soaring through the scenes.

The most ambitious sequence was a four-minute voyage through the Orion Nebula, a spectacular region of dust and gas within our galaxy that is approximately 15 light-years across. During the journey, viewers travel through bright and dark gaseous clouds, thousands of stars—including a
A grouping of bright, supermassive stars called the Trapezium—and embryonic planetary systems. The tour ends with a detailed look at a young circumstellar disk that is much like the structure from which our solar system is believed to have formed 4.5 billion years ago.

For some of the sequences, Institute imaging specialists developed new techniques for transforming the *Hubble* pictures into 3D. One of these involved splitting an image of a giant gaseous pillar in the Carina...
Nebula into multiple layers to give the structure three-dimensional depth. In another sequence, where viewers “fly” into a field of 170,000 stars in the giant star cluster Omega Centauri, a stellar database was used to generate a synthetic star field in 3D that matches recent, detailed Hubble photos. In each case, the sequences were carefully created to ensure scientific accuracy—to resemble closely the way scientists believe the represented objects would actually appear.

The film’s final four-minute sequence takes viewers on a voyage beyond the Milky Way, past many of Hubble’s most memorable images of galaxies, and deep into space. Some 15,000 galaxies from Hubble's deepest photographic surveys are seen to stretch billions of light-years across the universe in 3D. The view dissolves into a cobweb that traces the universe’s large-scale structure, the backbone of dark matter along which the galaxies were formed.

Rendering the image files developed at the Institute was an enormous computational effort, as well as an artistic challenge. Working with the giant Hubble image files required harnessing the collective processing power of 20 computers. The team rendered the files at 21 million pixels per frame, 24 frames a second, for a film approximately 3 minutes long. This equates to several hundred billion pixels—about as many pixels as there are stars in the Milky Way galaxy.

These science images were interwoven with scenes taken by the servicing mission astronauts using the IMAX 3D camera mounted in the Shuttle’s payload bay. The STS-125 crew also captured footage from inside the Shuttle using standard, high-definition cameras. This footage was then digitally upsized to match the large-format IMAX film. Hubble 3D also recounts the shuttle missions that deployed and then serviced the observatory. It includes footage shot for IMAX’s 1994 Destiny in Space, which showed the 1990 Hubble deployment, and film taken during the 1993 Servicing Mission flight to correct the effects of the telescope’s spherical aberration.

The world premiere of Hubble 3D took place at the Smithsonian National Air and Space Museum on its five-story IMAX screen on March 9, 2010. The crew of the STS-125 mission participated in the debut along with other prominent dignitaries. By the end of 2010, approximately 2 million viewers worldwide had seen the movie, which received glowing reviews from critics and audience members alike.

The film includes 3D fly-throughs of such iconic Hubble images as (bottom, left to right): the Eagle Nebula, Saturn and its aurora, the colliding galaxies known as “the Mice,” and the Helix Nebula. One of the most dramatic 3D sequences of the movie is a journey into the Orion Nebula (background). A 500-million pixel image of the nebula was used to create this sequence.
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.

Pre-Planetary Nebula IRAS 23166+1655
A striking, spiral-shaped, pre-planetary nebula known as IRAS 23166+1655 was recently imaged by Hubble’s Advanced Camera for Surveys. The nebula is found encircling the binary star LL Pegasi, which itself is hidden at optical wavelengths behind a thick cocoon of dust.

Astronomers believe the unusual spiral pattern is formed by the dynamic interaction between components of a binary star system. One member, a red carbon star, is losing material as it circles in a mutual orbit with a bluer companion star. The lost material forms a spiral, currently wrapped around the system four to five times, and moving outward at a speed in excess of 32,000 miles per hour. By combining this speed with the observed distance between the layers, astronomers calculate the thin spiral arms are each separated by 800 years of motion. The spacing between layers directly reflects the orbital period of the two stars, also estimated (by other means) to be approximately 800 years.

Stars that begin to form planetary nebulas around themselves have reached a significant milestone in their aging process. For them, the ejection of their outer layers indicates the beginning of their death throes. Massive stars don’t go through this phase, but collapse and explode as supernovas when their nuclear fuel runs out. But stars ranging from a half solar mass (half that of our Sun) to eight solar masses do not explode as supernovas at the ends of their lives. Instead, they begin to shed their outer layers of gas—typically in spatially asymmetric and temporally irregular ways. The complicated movement of this gas into space creates striking and intricate structures over time—especially if more than one star is involved, and multiple episodes of mass shedding occur. Spiral nebula IRAS 23166+1655 is a rarely seen example of a star just beginning this process.
A Disrupted Planetary System: Upsilon Andromedae A

Astronomers have known for more than a decade that three Jupiter-type planets orbit the yellow-white star Upsilon Andromedae A, the larger member of a wide binary star system. Now, with the help of Hubble, they have discovered that the star’s planets do not all orbit in the same plane—in contrast to how the major planets in our solar system circle the Sun. While the orbital inclination of the innermost planet is not yet known, the other two planets have orbits inclined by 30 degrees with respect to one another. This was a surprise.

The standard model for star and planet formation theorizes that a large cloud of mostly hydrogen gas laced with dust collapses to form a star. Planets subsequently condense from leftover material that swirls into a flattened disk around the star. Planetary orbits, therefore, should be coplanar. All eight of the major planets in our solar system orbit the Sun in this way. The outermost dwarf planets, like Pluto, have more inclined orbits, but these are thought to have been influenced by Neptune’s gravitational pull, as they are not close enough to the Sun to be as strongly controlled by the Sun’s gravitational field.

The Upsilon Andromedae A system could change astronomers’ thinking about how planetary systems typically form and evolve. Within
the standard model, its discovery suggests that violent events can disrupt planets’ orbits after a system forms.

Several different scenarios have been proposed that could produce the observed results. One is “planet-planet scattering,” which occurs when two planets gravitationally interact or physically collide with one another and move from their previous orbits. Another is disruption from a nearby star, like A’s binary companion—a red dwarf called Upsilon Andromedae B. This companion could itself have caused planet-planet scattering by gravitationally perturbing the system and creating orbital instability within it. Less likely is a third idea that disruptive interaction occurred from the inward migration of the planets due to drag caused by thick gas and dust within the circumstellar disk. If planetary migration did occur, this would most likely affect both the inclinations and the shapes of the planetary orbits involved.

The research on Upsilon Andromedae A actually marks the first time that the mutual inclination of two planets orbiting another star has been measured. Combining complementary data from Hubble and ground-based telescopes, astronomers also determined the exact masses of two of the three known planets. Additionally, they uncovered clues that a fourth planet orbits Upsilon Andromedae A at a much greater distance.

This system highlights—and adds to—the wide diversity astronomers have discovered in the sizes and locations of planets around other stars. These findings indicate the need for a better understanding of how planets form and interact. A key question to answer is whether the coplanar shape of our own solar system is the exception or the rule.
**Spherical Supernova Remnant**

*Hubble* recently imaged a spherical bubble of gas that is the visible remnant of a powerful stellar explosion, or supernova, that took place in the Large Magellanic Cloud (LMC)—a small galaxy about 160,000 light-years from Earth. Called SNR 0509-67.5, the bubble can be seen because an expanding blast wave from the supernova is slamming into the gas between the stars in the LMC, heating it up, and ionizing it. Ripples in the bubble’s surface may either be caused by subtle variations in the density of the ambient interstellar gas, or by pieces of the supernova’s ejected material. The gas shell is 23 light-years wide and is expanding at more than 11 million miles per hour.

Astronomers have concluded that the explosion was characteristic of an especially energetic and bright variety of supernova. Known as a Type Ia, researchers think such detonating stars arise from a white dwarf star in a binary system. If the white dwarf robs its partner of material and takes on more mass than its internal structure can support, the dwarf collapses and then undergoes a runaway nuclear reaction that causes it to explode. *Hubble’s* Advanced Camera for Surveys observed the supernova remnant on October 28, 2006 using a filter that isolates light from the glowing hydrogen seen in the expanding bubble. Astronomers then combined those observations with visible-light images of the surrounding star field taken on November 4, 2010, by *Hubble’s* Wide Field Camera 3.

---

*The supernova remnant SNR 0509-67.5 was imaged by Hubble’s Advanced Camera for Surveys. (See larger image opposite the Table of Contents.)*
Searching for Trans-Neptunian Objects

Countless icy rocks known as trans-Neptunian objects (TNOs) reside beyond the orbit of the giant ice planet Neptune. Scientists think that most of these objects are leftover material from the formation of the solar system planets. Their small size and low reflectivity make them faint and difficult to find. Using innovative techniques to cull Hubble’s data archive, astronomers have now added 14 new TNOs to the catalogue of more than a thousand such objects. These newfound bodies range in size from 25 to 60 miles across. To locate them, astronomers wrote software that analyzes hundreds of archival Hubble images and hunts for the streaks of light that these objects leave in time-lapse exposures as they travel through space.

The 14 TNOs, including one binary system, have visual magnitudes between 25 and 27 on the logarithmically-based astronomical brightness scale, making them more than 100 million times fainter than objects visible to the unaided eye. All 14 were found within five degrees of the ecliptic plane, the plane of the solar system planets. By measuring the objects’ motion across the sky, astronomers calculated each one’s orbit and distance from the Sun. They were then able to estimate the size of the TNOs by combining the measurements of each one’s distance, brightness, and estimated reflectivity. This study examined only one-third of a square degree of the sky. This means that there is much more space to explore, both near the ecliptic plane where these were found, and farther above and below it. Astronomers hope to find hundreds of additional TNOs using this new technique.

This image shows an artist’s concept of a trans-Neptunian object.
Assisting the Mission to Vesta

*Hubble Space Telescope* images of the large asteroid Vesta are being used to refine plans for the rendezvous of NASA’s *Dawn* spacecraft with this solar system body in July 2011. Scientists have constructed a video from the images that will help *Dawn*‘s operators improve the pointing instructions for the spacecraft as it is placed in a polar orbit around Vesta. The goal of the *Dawn* mission is to take pictures of the entire surface of the asteroid and measure the elevation of features over most of its surface to an accuracy of about 33 feet.

Analyses of the *Hubble* images revealed a tilt of Vesta’s pole, known to astronomers as its inclination, of approximately four degrees more to the asteroid’s east than was previously thought. The newly measured inclination implies that the seasonal changes between Vesta’s southern and northern hemispheres may take place about a month later than previously expected. This, in turn, results in a change to the pattern of solar illumination on the asteroid, a key ingredient for *Dawn*‘s imaging and mapping campaign.

The images also show differences in brightness and color on the asteroid’s surface. These characteristics hint at the large-scale features that the *Dawn* spacecraft will encounter when it visits the potato-shaped asteroid. Vesta is similar to the Moon, with darker regions of ancient lava beds and lighter orange-tinted areas of powdery debris—the pulverized remains of large meteor impacts. The flattened area on one end of Vesta—visible in the top row of images—is a giant impact crater formed by a collision billions of years ago. The crater is 285 miles across, which is close to Vesta’s diameter of roughly 330 miles. Vesta is similar in size to the state of Arizona. *Hubble* can resolve features on the asteroid as small as approximately 25 miles across, even though the asteroid is located 131 million miles from Earth.

*Each of the four Hubble images shown here presents a different view of Vesta over the course of its 5.34-hour rotation period. Astronomers used a total of 446 Hubble images, accompanied by additional ones from ground-based telescopes, to clarify Vesta’s rotational characteristics.*
Gas Funneling in Galaxy NGC 2976

Astronomers have long thought that gravitational interaction between galaxies during grazing encounters can cause the funneling of gas into a galaxy’s core. *Hubble* observations of galaxy NGC 2976 provide the clearest evidence yet of this phenomenon. The new observations show that star formation in the outer regions of NGC 2976 shut down millions of years ago due to a lack of gas, and is now confined to the innermost 5,000 light-years around the galaxy’s core. Astronomers attribute this to tidal interaction with the neighboring M81 group of galaxies. This interaction stripped some gases from the outer parts of the NGC 2976 and caused the remaining gases to lose angular momentum and fall inward, simultaneously igniting star birth within NGC 2976 but terminating it at its outermost edges.

Located about 12 million light-years away in the constellation Ursa Major, this galaxy’s relatively close proximity to Earth allowed *Hubble*’s Advanced Camera for Surveys to resolve hundreds of thousands of individual stars. This enabled astronomers to determine their colors and brightnesses, which indicate when the stars formed. What appear as blue dots in the image are fledgling blue giant stars residing in the remaining active star-birth regions.

Simulations predict that the same “gas-funneling” mechanism may trigger starbursts in the central regions of other dwarf galaxies that interact with their larger neighbors. The key to studying this process in detail is the ability to resolve many individual stars within galaxies, as is possible with *Hubble*. This allows astronomers to create an accurate overall view of the galaxies’ star-formation histories.
**Tactile Astronomy**

If you could touch a gaseous nebula, how would it feel? What about a bubble in space? These are some of the questions Max Mutchler, a research and instrument scientist at the Space Telescope Science Institute, and Noreen Grice, a pioneer in designing tactile astronomy images for the blind, pondered as they embarked upon an effort to create a touchable image of the Carina Nebula. Their goal was to produce a useful and intriguing image that would serve the visually impaired, as well as sighted people who have kinesthetic learning styles.

Believing astronomy to be a visual science in which they could not participate, sight-impaired youth have often felt uninvited or excluded from the subject. Mutchler’s aim is to entice them back by convincing them otherwise. In truth, much of full-spectrum astronomy involves converting invisible wavelengths of light into something we can experience with our senses. One can as easily translate this invisible light into tactile “images” sensed with our fingers as false-color images seen with our eyes.

Mutchler conceived the idea when he received an archival research grant to work on large mosaic images of the Carina Nebula—a gigantic, 3-million-year-old cloud of dust, gas and stars located 7,500 light-years from Earth. Scientifically valuable because of its relative proximity to Earth, the nebula is home to thousands of stars that together present a complete picture, from birth to death, of the stellar life-cycle. Mutchler applied for and was awarded a NASA Education and Public Outreach grant to pursue the tactile astronomy initiative.

Because the nebula is so vast and rich, designing a textured image that conveys its full beauty and complexity was somewhat daunting. Choosing exactly which features to include on the textured image surface was a big challenge. Grice, president of You Can Do Astronomy, LLC, and author of several touchable astronomy books, applied a lesson she had learned from the publication of her book, *Touch the Universe*: less is more. A picture cluttered with too many tactile details is overwhelming to the mind’s eye. She and Mutchler decided to provide just enough texture to convey the idea, and augment this with Braille text to explain the science and describe the scene.
Mutchler and Grice decided to make the focal point the Keyhole Nebula, a portion of the larger Carina Nebula observed and named by the 19th century English astronomer John Herschel. They included the important features needed to tell the story of stellar life and death—pillars of gas and dust that harbor infant stars, a cluster of young stars called Trumpler 14, and a massive, unstable star near the end of its life named Eta Carinae. They embossed the image with lines, slashes, and other markings that correspond to objects in the giant cloud—enough tactile signals for the visually impaired to form a picture of the nebula in their minds. The two then developed a legend identifying the raised features and wrote short, guided Braille explanations along with a supporting audio tour that provides more information on highlighted features.

Mutchler and Grice unveiled the tactile Carina Nebula image booklet in January 2010 at the American Astronomical Society meeting in Washington, DC. It consisted of two panels: one contained a tactile color

![Carina Nebula texture legend](image)

This tactile image booklet on the Carina Nebula consists of a tactile color image and a braille texture legend.
image; the other, a textured legend. Mutchler made 300 copies of the booklet and continues to distribute them to organizations that serve the visually impaired, including state schools, libraries for the blind, and the National Federation of the Blind located in Baltimore, Maryland.

This initial outreach effort has led to a monthly feature called “Tactile Astronomy” on *Hubble’s Amazing Space* website. It offers a collection of downloadable, “do-it-yourself” images that can be printed in a tactile format on a thermal expansion paper machine. These specially prepared files include Braille titles and embedded audio that describe the featured celestial object and what astronomers are learning about it. The growing collection began with the first images released after *Hubble* Servicing Mission 4 and now includes many different areas of astronomy. These unique images have become popular with both teachers and students alike.

Barred spiral galaxy NGC 6217 is one of the monthly Tactile Astronomy subjects on *Hubble’s Amazing Space* website. Designed to be printed on a thermal paper expansion machine, these files include Braille titles and are accompanied by embedded audio. NGC 6217 was the first astronomical object observed with the refurbished telescope after *Servicing Mission 4.*