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The Hubble Space Telescope, from tragedy to triumph.

With all of the technology available today, there is still one factor that severely interferes with Earth-based telescopes: the atmosphere. Heat waves rising from the Earth's surface distort light waves as they enter the atmosphere. Light pollution and particles in the atmosphere also hinder the ability of even the largest and most complex telescopes on the ground. The Hubble Space Telescope was designed to solve this problem. Although nearly declared a complete failure and technological nightmare to the space program, engineers and scientists have brought Hubble up to the task for which it was intended, to see farther and better than any Earth-based telescope ever could. Hubble has achieved this goal, and more, forever changing the way scientists and astronomers view the Universe.

The Hubble Space Telescope was named after famed scientist and Astronomer Edwin Powell Hubble, 1889-1953. By the age of 30 Hubble had an undergraduate degree in astronomy and mathematics, and would later earn a PhD in astronomy. In 1924, while working from the Mt. Wilson Observatory in California studying nebulae, Hubble announced the discovery of a variable star in the Andromeda Nebula. By using methods already in place he calculated that the distance to this star was much farther than anyone had realized, in fact that the nebula itself did not reside within our own galaxy. This was a major discovery since it was common belief that very little existed outside of our Milky Way. Suddenly the Universe was much, much larger. Hubble also worked to classify these far-away galaxies according to their content, distance, shape, and brightness. By observing redshifts[1] in the light wavelengths emitted from these galaxies, he determined that the galaxies were indeed moving away from one another at a rate related to the distance between the galaxies (later dubbed "Hubble's Law"). The Universe is expanding! Based on this discovery, the point where the expansion started was calculated, and provided strong evidence to support the Big Bang theory. Hubble originally calculated the event to have happened about 2 billion years ago, however more recent estimates put it at about 20 billion years ago (Edwin Hubble 1889 – 1953).

The concept of putting a telescope in Earth's orbit dates back to 1923, when rocket scientist Herman Oberth published an article that suggested placing a telescope in space (Historical Timeline). Another scientist interested in putting a telescope in space was astronomer Lyman Spitzer (Peterson and Brandt 18). In 1946 Spitzer wrote:

> Most astronomical problems could be investigated more rapidly and effectively with such a hypothetical instrument than with present equipment. However, there are many problems which could be investigated only with such a large telescope of very high resolving power. It should be emphasized, however, that the chief contribution of such a radically new and more powerful instrument would be, not to supplement our present ideas of the universe we live in, but rather to uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time. (Quoted in Peterson and Brandt 19)

Nancy Roman, NASA's Chief of Astronomy at the time, referring to Spitzer's statement said, "Basically, Spitzer proposed what really was LST [Large Space Telescope] back in 1946, but I don't think anybody took it seriously until 1962" (Quoted in Peterson and Brandt 19).

In 1977 Congress approved funding for the Hubble Space Telescope program, and named the instrument in honor of Edwin Hubble.

In 1981 the Space Telescope Science Institute was built in Baltimore, Maryland as the astronomical research center for the Hubble Space Telescope program. The Institute remains heavily involved with the Hubble Space Telescope program (Historical Timeline).

The Hubble Space Telescope was originally scheduled for launch in the fall of 1986, until January 1986 when the Space Shuttle Challenger exploded in mid-flight, killing all crew members aboard. The disaster grounded all shuttle flights for almost three years (Anatomy of a Satellite Delay). Investigations have shown that low temperature conditions at the time of launch caused an O-ring that seals sections of the Solid Rocket Booster (SRB) to fail, causing extremely flammable combustion gases to leak from the SRB (Cause of the Accident).

The mission to deploy the Hubble Space Telescope aboard the Space Shuttle Discovery, Space Transportation System 31 (STS-31), was originally scheduled for March 26, 1990. In February of 1990 a motor replacement pushed the launch date back to April 12, 1990. On April 2, 1990, after performing a flight readiness review, NASA moved the launch date up to April 10. The launch date was once again pushed back to April 25 in order to replace an auxiliary power unit and to allow time to re-charge Hubble's batteries. On April 18 the launch date was moved up one day to April 24, after proper operation of the replacement auxiliary power unit was verified (Launch Date Rescheduled). The Space Shuttle Discovery mission STS-31 was launched at 7:33:51 a.m. CDT on April 24, 1990, after a three-minute delay to troubleshoot a liquid oxygen valve. Discovery was maneuvered to a 331 x 332 nautical mile orbital altitude. Communications were verified with the telescope while it was still being powered from Discovery. The telescope's power was transferred from Discovery to its internal batteries at 7:37 a.m. CDT on April 25, 1990, just over a day into the mission. Astronauts began slowly maneuvering the telescope out of the shuttle's cargo bay at 7:45 a.m. CDT. The telescope's batteries were capable of powering the instrument for eight hours. Once the telescope's solar panels were unfurled they would power the telescope and keep the batteries charged. Some problems were encountered, but after several attempts both solar panels were successfully deployed by 2:03 p.m. on April 25. The panels successfully powered the telescope and charged its batteries. The telescope's two high-gain communications antennas were also successfully deployed. The telescope was released from Discovery's manipulator arm at 2:37 p.m. CDT on April 25, 1990. Discovery was then maneuvered to a position of about 4 nautical miles away from the telescope. The shuttle would remain in this position until the aperture door of the telescope was opened, exposing the telescope's optics to the universe. Hubble's aperture door opened successfully at 8:46 a.m. CDT on April 27, 1990, three days into the mission. The Discovery crew was released from support of the Hubble Space Telescope at about 9:30 a.m. CDT on April 27. The message was delivered to the crew from spacecraft communicator Story Muskgrave, "Discovery, Hubble is open for business". Discovery landed safely at Edwards Air Force Base in California at 6:49 PDT on April 29, 1990 (Discovery Status Reports).

With typical ground-based telescopes, an observer would usually simply look into an eyepiece to view the telescope's target image. Obviously, this was not possible with Hubble. Several scientific instruments were installed aboard Hubble to capture various types of images and relay the image data to observers on Earth. The five original science instruments were the Wide Field and Planetary Camera (WF/PC), the Faint Object Camera (FOC), the Goddard High Resolution Spectrograph (GHRS), the Faint Object Spectrograph (FOS), and the High Speed Photometer (HSP). Two methods of mounting the science instruments were used, radial mount and axial mount. Radial instruments are mounted perpendicular to the body of the telescope, inserted through a door in the side of the telescope behind the main mirror. Axial instruments are mounted in parallel to the axis of the telescope behind the main mirror. The WF/PC, Hubble's only radial instrument and the most used, is sensitive to light wavelengths ranging from ultraviolet to infrared, including the entire spectrum of visible light. The WF/PC uses two sets of four Charge Coupled Devices (CCD) to capture images. The four different CCD images are then "pasted" together electronically to provide a full picture. The WF/PC was built by the NASA Jet Propulsion Laboratory in Pasadena, CA. The FOC is sensitive to light in the red-to-ultraviolet range, from 1150 to 6500 angstroms[2] in wavelength. It contains two complete detector systems with image intensifiers to gather as much light as possible from faint, distant objects. The FOC is so sensitive that if it needs to observe anything relatively bright, it must use filters to prevent saturating of the instrument's optical detectors. The FOC was funded by the European Space Agency and its design was the responsibility of H.C. van de Hulst of the Leiden Observatory in the Netherlands. The GHRS is sensitive to only ultraviolet light. Users of the GHRS can select specific wavelengths to study between 1150 and 3200 angstroms. The GHRS has three resolution modes, and is capable of resolving features from 1 to 0.02 angstroms wide. The GHRS was built by Ball Aerospace in Boulder, CO. The FOS is also an ultraviolet sensitive instrument. It has a wider range of wavelength sensitivity than the GHRS, 1100 to 8000 angstroms. The FOS can study fainter objects than the GHRS, but has a lower resolution than does the GHRS. It has two modes of resolution, low resolution mode can resolve features 15-20 angstroms wide and high resolution mode can resolve features 3-4 angstroms wide. The FOS takes the "big picture" and the GHRS focuses in on the finer details. The FOS was built by Martin Marietta Astronautics Group of Denver, CO. The HSP was designed to measure high speed variations of light intensity from high energy objects of the universe. The HSP could take up to 100,000 samples per second. Because of its fast sample rate, it was very sensitive to any small movements, or jitter. The HSP was Hubble's only original university built instrument, built by the University of Wisconsin. The FOC, FOS, GHRS, and HSP are all axial instruments (Peterson and Brandt 62-72).

As with the first sailing of a new ship, or the first flight of a new aircraft, the viewing of the first images from a new telescope is a special event. Usually this is a relatively private moment, since the very first images are usually not of the expected quality. The scientists and astronomers do not want the press to see these sub-quality images, until the "bugs" are worked out of the system. This event is known as 'first light' (Peterson and Brandt 2). Scientists even went as far as to prepare everyone for disappointing images, explaining that an instrument so complex would not be easy to operate. Astronomer Holland Ford was quoted as telling reporters "It's a safe prediction that not everything will work.", after the shuttle launch. Even with the presumptions that problems are going to happen, the scientific community, as well as the general public, was overly excited and waiting to be amazed by the spectacular images expected to be delivered by Hubble. Moments after the first light from a star cluster in the constellation Carina streamed into the telescope, the image appeared on the monitors at the Space Telescope Science Institute. The image looked like a group of dots on a gray screen (3). While the team that operates the camera that took the image was processing the image with computer programs, a sense of excitement spread through the group of people that were waiting to see the processed image. Applause broke out as the image of a star cluster took shape. Shouts of “Look at that!” and “It works! Hubble works!” filled the room. Although the image was not of great quality, as expected, the image was hailed as a success by the press. Everyone knew that the telescope would need some focusing adjustments, but the telescope worked. However, members of the camera team that snapped the image were not so satisfied with Hubble’s first image. The team knew that something was not right. Besides the image quality, other problems were showing up with the telescope. Hubble’s guidance system was not locking onto it’s targets properly (5). One of Hubble’s solar panels was flapping and causing the telescope to move around more than it should. These problems were fixable, the concern was in the un-focused nature of the image captured by the telescope. Scientists kept their concerns regarding the focusing ability from the press. As far as the press knew the problems with the telescope were expected and relatively easy to correct. However, grapevine rumors of a serious optical problem were quickly spreading among insiders. During a meeting on the day after ‘first light’, Hubble team member, astronomer, and optical expert Roger Lynds spoke up and said he thought the telescope had a “serious spherical aberration problem”. Those attending the meeting dismissed Lynds’ suggestion. However, a Space Telescope Science Institute scientist almost immediately came to the same conclusion upon examining the first image from the telescope

(6). Computer simulation models confirmed everyone's worst fear, as did the first image from a different camera, the telescope was in fact suffering from spherical aberration (9).

The Hubble Space Telescope is of a conventional reflector design. Parallel light waves enter the telescope and are reflected off of a primary mirror. The primary mirror is curved, reflecting the light waves into a "cone" shape, to a secondary mirror that is much smaller than the primary mirror. The secondary mirror is also curved, reflecting and focusing the light waves to a focal point, through a small hole in the center of the primary mirror, as shown in Figure 1 (Hubble's Amazing Optics). The relationship of the diameter of the mirrors to the curvature of the mirrors must be such that when the light waves finally reach the focal point, all of the different light waves hit the focal point in a very small area, almost a single point. Investigations revealed that Hubble's primary mirror was not ground to the correct specifications. There was not enough curvature to the primary mirror, shown in Figure 2. The 94.5 inch diameter mirror was ground 4 microns (0.000004 meters, 0.000157 inches, or about 1/50th the thickness of a human hair) too flat. The result is instead of one focal point for all light waves, there are many different focal points, at differing distances from the secondary mirror, as shown in Figure 3. Only the waves reflecting from towards the center of the mirror were focused at the correct focal point. The waves reflecting from the outer edge of the mirror were not focusing at the correct focal point. This is known as spherical aberration (Eyeglasses for Hubble).

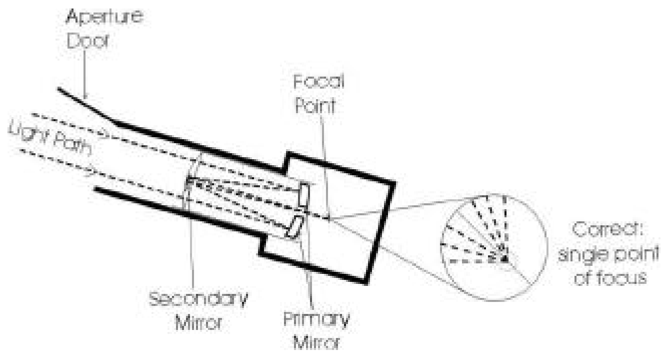

Figure 1 Basic optical design (Hubble's Amazing Optics)

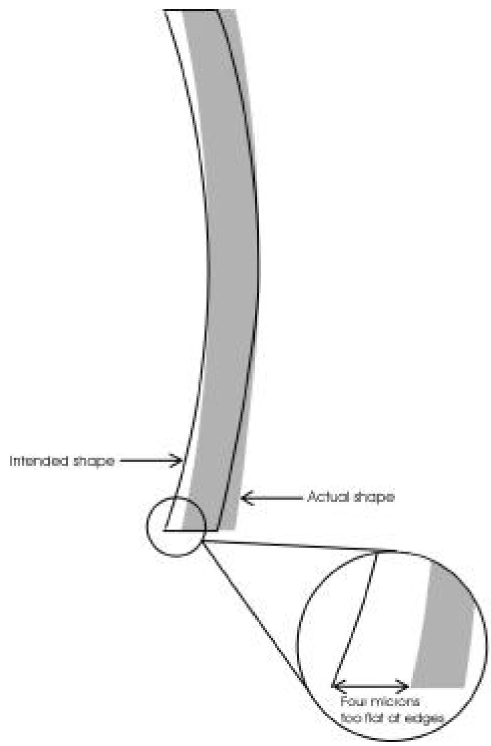

Figure 2   Primary mirror too flat (Eyeglasses for Hubble)

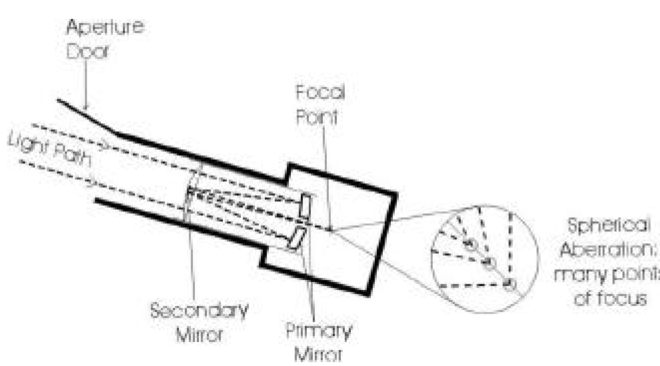

Figure 3 Spherical Aberration (Eyeglasses for Hubble)

It was later discovered that a small spot of non-reflective paint had worn off of a device used in the positioning of the primary mirror during manufacturing. The lack of paint caused a measurement beam of light to reflect when it was not supposed to. This error caused technicians to position the mirror improperly when testing the shape of the mirror (Peterson and Brandt 13).

The discovery of the flawed primary mirror started a swarm of demeaning media headlines, finger pointing and accusations. NASA's reputation was rapidly declining. Then Senator Al Gore in an angry statement, referencing the Space Shuttle Challenger tragedy, summarized the impact this discovery would have to NASA's future projects, "This is the second time in five years that a major [NASA] project has encountered serious disruption by an inherent flaw that was apparently built into the project as much as ten years before launch and went undetected by NASA's quality-control procedures." Further stating the lack of faith in NASA's abilities, Gore added, "The implications for the space station and the Moon-Mars effort, and for other large missions, are really quite significant." (Quoted in Chaisson 189). NASA, however was already making plans for repairing the telescope's impaired focusing ability. Although the Hubble Space Telescope was designed to receive periodical servicing missions via Space Shuttle missions, neither the primary nor the secondary mirror could be replaced in orbit (Chaisson 184). Too bad, since a backup mirror was produced by Eastman Kodak company, that was certain not to have the same design flaw (Chaisson 226). Instead, modifications could be made to second-generation instruments, already being designed to replace the initial measuring instruments. Since the image-gathering instruments already use a mirror to reflect the focused light into the instrument, replacement instruments can be fitted with mirrors that for the most part correct the spherical aberration problem introduced by the primary mirror. The replacement instrument's mirrors would introduce an aberration of equal magnitude, but of opposite polarity, thus canceling the effect of aberration produced by the primary mirror, similar to using glasses or contact lenses to correct a person's eyesight. The estimated cost of adding the corrective mirrors was not considered significant, since the replacement instruments were already planned. Provided that the amount of aberration could be accurately measured, it was estimated that Hubble would be able to focus nearly 70 percent of the light it captured to within 0.1 arc-second resolution. This would achieve the original goals of the telescope (Chaisson 184). This relatively simple and easy to implement solution was enough to start raising spirits among astronomers and the people involved in the program. Others started suggesting using the telescope in it's current state to observe more easily viewable objects, such as bright, dense star clusters and the planets within our solar system. Using computer enhancement methods, Hubble could still make useful scientific observations.

The do-or-die nature of the Hubble repair mission was summarized in a statement by a senior Hubble manager still with the program in 1993, the year the repair mission was launched, Ed Weiler, "Whether we like it or not, this [Hubble Space Telescope] program is going to become a national triumph or a national tragedy" (Quoted in Chaisson 355).

During the 1980s when the instrumentation for the telescope was being designed and built, Hubble team members built an empty, backup instrument housing to be used aboard Hubble in the event any of the axial science instruments could not be launched with the telescope. Engineers decided to use this box, labeled Space Telescope Axial Replacement (STAR), to house a set of corrective mirrors that would correct for Hubble's main mirror spherical aberration flaw (Chaisson 359). The mirrors would be shaped and polished such that they would introduce an equal but opposite amount of aberration, thus canceling the aberration introduced by the primary mirror and effectively correcting the telescope's vision (Chaisson 357). Given the corrective nature of the STAR, the prefix CO was added to indicate corrective optics, changing the name of the device to the now infamous COSTAR. Actuator pistons were attached to the mirrors to allow for precise positioning. The installation of COSTAR has been compared to contact lenses or glasses used to correct the vision of a near-sighted person. This correction however would only work for the axial instruments of the telescope (Chaisson 359). Hubble's main radial instrument, the Wide Field and Planetary Camera (WF/PC), would not benefit from the corrective optics of COSTAR. This turned out not to be of much concern, since the camera had already been scheduled to be replaced on the first servicing mission with WF/PC-2. When the primary mirror flaw was discovered, it was realized that the camera's small relay mirrors could be shaped to correct for the aberration introduced by the primary mirror, in the same way that COSTAR corrected the aberration for the axial instruments (Chaisson 357). Of course, there was a trade-off. In order to install the vision-repairing COSTAR, one of the existing axial instruments had to be sacrificed to make room for the telephone-booth sized device. After some political debate, and because it was scheduled to be the least frequently used of Hubble's original scientific instruments, it was decided that Hubble's High Speed Photometer would be permanently removed to make room for COSTAR (Chaisson 359). Some of the observations that were intended to be performed by the High Speed Photometer included the measuring of variations expected for light being "sucked" into a black hole, and timing of the slow-down of pulsars, rapidly rotating "dead" neutron stars (Chaisson 360).

On December 2, 1993, in what has been described as a spectacular nighttime fireball, Space Shuttle Endeavor mission STS-61 was launched from the Kennedy Space Center. On December 4 Endeavour rendezvoused with Hubble at an altitude of about 356 miles, some 25 miles lower than when the telescope was released into orbit. Since Hubble was designed with regular servicing missions in mind, astronauts had no trouble grappling the telescope and attaching it to the specially built platform of the shuttle's cargo bay (Chaisson 360). In addition to COSTAR and WF/PC-2, other repairs scheduled were the replacing of all of Hubble's faulty gyroscopes[3], some computer and memory upgrades, and a new set of solar arrays (Chaisson 356). Over a period of five days, while the world watched, astronauts put on a remarkable show high above the Earth. They managed to accomplish what anyone hardly thought possible, even themselves, in successfully completing all of their main objectives with only a few small problems (Chaisson 361). The mission went so well that the astronauts were also able to perform other lesser priority tasks. The STS-61 Hubble repair mission was one of the most sophisticated ever performed. Lasting almost eleven days the crew made five Extra Vehicular Activity (EVA) sorties (spacewalks), the most ever performed during a shuttle mission. The flight plan had allowed for two additional EVAs, but they turned out to be not necessary. STS-61 astronauts performed the second longest spacewalk in NASA history at 7 hours and 50 minutes. Endeavour safely landed at Kennedy Space Center at 12:26am on December 13 (Historical Timeline).

The first observation attempt after the servicing mission did not go so well. A repair kit for the GHRS that was installed was apparently faulty. The power supply that was to repair a failure of the instrument years earlier caused the instrument to completely shut down. Knowing that the program absolutely needed some good news if it were to survive, NASA cancelled all scheduled tests of the GHRS (Chaisson 362). Scientists turned their attention to the newly installed WF/PC-2 with it's own corrective optics (not influenced by COSTAR). When the first image settled on the screen the improvement in Hubble's eyesight was immediately obvious. Most of the blurriness that was caused by the aberration of the flawed primary mirror was gone. The corrective optics worked. An estimated 55 percent of a star's light was being concentrated in the focal point, not the 70 percent that was the original goal, but a tremendous improvement over the 15 percent before the repair. This was before any adjustments of the corrective mirrors, which was sure to improve the performance of the telescope (Chaisson 363). The performance of COSTAR was even better. Images taken with the FOC showed that the amount of light that was focused properly went from 15 percent (again, due to the spherical aberration problem) to an incredible 80 percent, much more than NASA's original specifications (Chaisson 366). Before the service mission Hubble's vision could reach out to 4 billion light years from Earth. After the repairs Hubble's vision had tripled, allowing the telescope to see up to 12 billion light years, possibly increasing as engineers and scientists performed fine tuning of the new optics. Many questions from the media started arising with the successful repair of the telescope, such as "What do you expect Hubble to tell us?", "How far back will we see in time?", "What do you expect to learn from Hubble?", "Do you really expect to see back to the beginning of time?" (Barbree and Caidin xix-xx). The positive results that came right away were exactly what the Hubble program needed to stay alive. NASA and the HST program were saved.

Hubble would not see human visitors again until servicing mission STS-82, Hubble Service Mission 2 (SM2), was launched aboard the Shuttle Discovery on February 11, 1997. Two instrument upgrades were installed, the Near Infrared Camera and Multi-Object

Spectrometer (NICMOS) and the Space Telescope Imaging Spectrograph (STIS) (Servicing Mission 2). The NICMOS would replace the FOS and the STIS would replace the GHRS (Hubble's Science Instruments). The NICMOS operates in the infrared range of wavelengths, 8000-25000 angstroms (Hubble's Instruments: NICMOS). The advantage of NICMOS is that it can see through clouds of gas and dust (Hubble's Science Instruments). The STIS is a combination instrument, combining a camera with a spectrograph. It covers a wider range of wavelengths, from near-infrared to ultraviolet. The spectrograph spreads out the light so that properties such as chemical composition, temperature, radial velocity, rotational velocity, and magnetic fields can be analyzed. The STIS has two modes of operation, one where many spectra are sampled and one where a single spectrum is sampled giving better wavelength resolution in a single exposure. The STIS also has the ability to block out light from bright objects that could interfere with nearby faint objects under observation (Hubble's Instruments: STIS).

The next Hubble mission took place in October of 1998. This was not technically an actual service mission since no work was actually done on the telescope itself. The HST Orbital Systems Test (HOST) mission aboard Shuttle Discovery STS-95 (the "John Glenn Mission) was to test the effects of radiation on hardware that was to be installed on the telescope. This hardware included an advanced computer, digital data recorder, and a cyrogenic cooling system. All tests results showed that the hardware would perform to expectations (Hubble Orbital Systems Test).

What was originally to be Hubble's third service mission, one of regular maintenance, turned into more of an emergency repair when the fourth of six gyroscopes failed in November 1999. Hubble requires at least three functional gyroscopes to be able to position itself properly. With only two working gyros, Hubble went into safe mode, rendering the telescope totally inoperative. Earlier that year when the third of the six gyroscopes failed, NASA decided to split the scheduled third service mission into two parts, SM3A and SM3B. SM3A was launched on December 19, 1999 aboard Shuttle Discovery STS-103. SM3A was developed and executed in 7 months, the quickest a shuttle mission had ever been put together. Astronauts successfully installed six new gyroscopes, six battery voltage/temperature improvement kits, a new main computer, a new digital data recorder, a new fine guidance sensor, and new insulation. The second part of the third servicing mission, SM3B, was scheduled for early 2002. (Servicing Mission 3A).

SM3B, the fourth and most recent visit to Hubble, launched on March 1, 2002 aboard Shuttle Columbia STS-109. On this mission Hubble's FOC was replaced with the Advanced Camera for Surveys (ACS) (Hubble's Science Instruments). ACS is comprised of three different cameras, each with specialized capabilities. As a whole the instrument can see light wavelengths ranging from visible to far into the ultraviolet range. A high resolution camera will take extremely detailed pictures of galaxies and nebulae, and search for existing and developing planets. A solar blind camera filters out visible light in order to concentrate on ultraviolet only. A wide field camera will conduct new surveys of the universe. The new ACS will be able to produce 10 times as many science results in the same amount of time than it's predecessor, the FOC. New solar array panels were also installed on this mission. The new panels are rigid arrays, not like the old ones which rolled up. The rigid arrays are more robust, and one-third smaller while delivering 30 percent more power. A new Power Control Unit (PCU) was also installed, taking full advantage of the new solar arrays. This required the telescope to be completely powered down for the first time since it's launch in

1990. A new cooling system, the NICMOS Cryocooler (NCC) was retrofitted to the NICMOS, which had become inoperative in 1999 after using up all of it's coolant. The experimental cooling system was tested during the 1998 HOST mission. The goal was to re-cool the NICMOS infrared detectors to -334 degrees F (-203 degrees C or 70 K), required to revive the instrument's infrared vision (Servicing Mission 3B). According to Rick Higgins, COS program manager at Ball Aerospace in Boulder, CO, to date the cooler has accomplished its goals as intended. On April 30 NASA released the first images from the ACS, one of which is a stunning image of a galaxy known as the Tadpole Galaxy. The name comes from a debris tail stretching 280,000 light-years from the galaxy, which is about 420 million light years away from us. The background of the image contains a countless number of galaxies and star systems, seen with the greatest clarity ever achieved (Fienberg, Richard).

Still in the preliminary stages, SM4 will deliver two new science instruments to Hubble. Hubble's workhorse, the WF/PC-2 will be replaced with the next-generation WF/PC-3. The new instrument will take advantage of the latest CCD technology and is expected to last for the life of the Hubble program. The second instrument, the Cosmic Origins Spectrograph (COS), will replace the now infamous COSTAR. The COS is a medium resolution spectrograph designed to operate into the near and mid ultraviolet wavelength range (Servicing Mission 4). SM4 is expected to be the last servicing mission to Hubble. Upon the installation of the WF/PC-3 and the COS, all science instruments aboard Hubble will be Ball Aerospace Boulder, CO built. SM4 is scheduled for launch in March 2004 (Higgins, Rick).

Hubble's replacement, the Next Generation Space Telescope, is already being designed and expected to be launched in 2009 (Next Generation Space Telescope). NGST's primary mirror will be a minimum of 20 feet in diameter (compared to Hubble's 8 foot mirror). It will monitor light in the visible to mid-infrared wavelength range and is expected to have a lifetime of five to ten years. The NGST will orbit at an altitude of 940,000 miles (1.5 million kilometers), requiring it to be launched with a medium-sized rocket taking about 3 months to reach orbit (Quick Facts). Of course the high orbit will make the NGST non-serviceable.

Since the repair of the flawed optics, Hubble has made some tremendous scientific contributions, not to mention countless breathtaking images. Early on, an observer using a ground-based telescope noticed what seemed to be a comet that had somehow been "crushed" into many pieces. These pieces made several large collisions with Jupiter, at least one creating an impact site larger than the planet Earth. Hubble also confirmed the existence of black holes, discovering several of them. Scientists also now have what they feel is a much more accurate calculation of the Hubble Constant, the rate at which the universe is expanding. Hubble also has allowed scientists to calculate a more accurate estimate of the age of the universe (Hubble: The First Decade). Recent discoveries continue to impress and amaze scientists and astronomers. Hubble has captured the incredible fireworks-like display of the explosion of a massive star, known as a supernova remnant. The light from this explosion first reached earth 320 years ago. The remnant lies 10,000 light years from Earth (Colorful Fireworks Finale). By pushing the limits of it's vision, Hubble has revealed the oldest burned-out stars in our galaxy. These very old, very dim stars provide a different method for determining the age of the universe, not relying on measurements of the expansion of the universe. These very old white dwarf stars are 12 to 13 billion years old (Hubble Uncovers Oldest "Clocks" in Space).

The Hubble Space Telescope program provides some classic examples of what not to do in a major engineering project. It also shows that through hard work, determination, and cooperation, a seemingly doomed project can be turned around and transformed into an overwhelming success. Unaffected by the observational effects of the Earth's atmosphere, Hubble has provided us with over a decade of scientific accomplishments.

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[1] Emitted light wavelengths increase as an object is moving away from an observer, thus making the light appear to be red in color. This is known as redshift.
[2] 1 angstrom is equal to 10^{-10} meters, or 0.1 nano-meter.
[3] Gyroscopes are devices used to position the telescope to point it at it's target for observation.

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