2. The Hubble Space Telescope: Trials and Triumphs

Mention the words 'space telescope' to someone, and chances are the name 'Hubble' will trip off his or her lips. For nearly three decades, the Hubble Space Telescope (HST) has, more than any other telescope in history, revolutionized our understanding of the cosmos and our place within it. Yet, it was no plain sailing for the famous telescope, as we shall explore in this chapter.

Although HST was not launched until the 1990s, the impetus for its development actually began during the Cold War back in 1959; just one year after the Soviets launched their famous Sputnik probe. The then-chairman of the Space Science Board of the National Academy of Sciences, Lloyd Berkner, solicited practical suggestions for space-based projects to follow those undertaken in the International Geophysical Year that lasted from July 1, 1957 through December 31, 1958.

The response was encouraging, with more than two hundred proposals being received. These were subsequently studied by NASA and its advisory committees and used to refine a space-based observatory program. After such an extensive consultation, it was agreed that the launch of a large Orbital Astronomical Observatory was a priority in the following decades.

The dream of launching anything as sophisticated as HST had to begin with much more modest endeavors, to verify the 'proof of concept' as it were. In this capacity, astronomers first endorsed the launch of a string of smaller telescopes covering a variety of wavebands (including visual) before concentrating on a truly large space-based observatory. While these smaller missions were ongoing, Boeing received a contract from NASA to initiate the outline design of a 3-meter (120 inches) aperture instrument simply called the Large Space Telescope (LST). This size of telescope was deemed the maximum that could be successfully launched into space using NASA's most powerful launcher, the Saturn V launcher,

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which was first developed for the famous Apollo manned missions to the lunar surface. At this early stage, it was also anticipated that the telescope would be developed as part of a manned orbiting space station, a vision widely shared by space scientists in the post Apollo era.

A panel of 100 scientists and engineers brought together by the Space Science Board and NASA gathered at Woods Hole in Massachusetts in 1965 to discuss possible future space missions. At this meeting, a strong consensus of opinion was formed on the development of LST and a commitment was expressed to develop new technologies to make such a space telescope possible. The science priority of LST was envisioned to be in the discipline of cosmology, where it would be used to measure the distances to galaxies too far to be imaged from the ground and redefine the Hubble constant and the age of the universe (see Box 1 for an overview of this science).

Box 1: Hubble's Law and the Expansion of the Universe

In 1929, the American astronomer, Edwin Hubble, published the results of his studies on the red shift of a number of distant galaxies. His work was based at the then state-of-the-art 2.5-meter reflector atop Mount Wilson in California. Based on his observations of 24 very bright, distant stars (Cepheid variables), Hubble was able to state a new relationship;

$$v = H_o \times d$$

where v is the relative velocity of the galaxy, d is the distance of the galaxy in meters and H_o is Hubble's constant in units of per second (s^{-1}). During Hubble's day, the constant was calculated to be $1.62 \times 10^{-17}\ s^{-1}$ but over the decades, after the accumulation of a much larger sample of galaxies, the Hubble constant was revised to its current value of $2.34 \times 10^{-18}\ s^{-1}$ (Fig. 2.1).

A possible explanation for this relationship is that one event caused the creation and emission of all the matter in

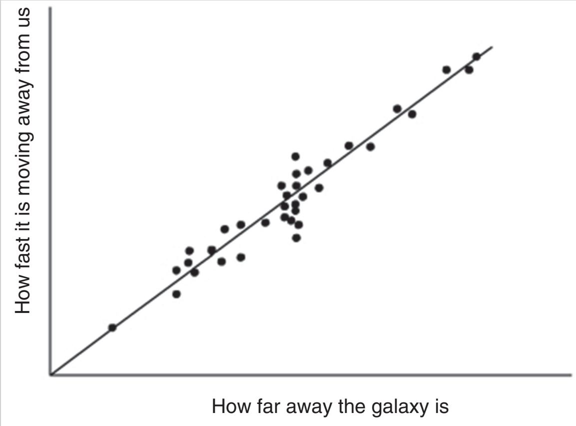

Fig. 2.1 Graph showing Hubble's Law (Image by the author)

the universe from a single point. This matter expanded exponentially, creating the universe as we know it today. Objects moving quickly are at extreme ends of the universe and relatively slower moving objects are closer to the 'center'. This would mean that observers like ourselves would see distant objects moving away from us. This recession velocity increases with distance, so that we would be moving away from slower objects nearer the center. From our observations, all galaxies appear to be moving away from us.

The Hubble constant has further use. The law suggests that the universe is expanding and if the rate of expansion is assumed to be fixed, then the Hubble constant may be used to determine the age of the cosmos.

Time = distance (d)/ speed (v), so Hubble's law gives $d/v = 1/H_o$.

Thus, $1/H_o$ yields the age of the universe. All recent measures place the age of the universe at around 13.8 billion years.

One of the biggest problems with getting LST up and going was to persuade a generally skeptical public that such a mission was worthwhile from an economic and scientific standpoint. In this capacity, the National Academy of Sciences Ad Hoc Committee on the LST convened a meeting in April 1966.

Chaired by the distinguished astronomer Lyman Spitzer, this committee cogitated on the relative advantages of sending a large astronomical telescope into space, as well as investing in a greater number and diversity of ground-based telescopes. By 1969, NASA officials had been convinced that there were sufficient funds to justify both approaches. In particular, the so-called Greenstein Report provided the cost estimate of launching a 3-meter class telescope into space—about $1 billion spread over a decade of time. Despite the Greenstein Committee's optimistic projections, Congress was less enamored by the project and refused to back the LST program. Furthermore, the approval of the Space Shuttle Program by NASA in 1972 meant that the most long-term commitments to space science had to be totally re-evaluated. This impelled astronomers Lyman Spitzer and John Bachall to take the opportunity and push the LST program forward since the Shuttle would provide new upgrades and replace components that a large orbiting astronomical observatory would eventually need.

A significant breakthrough was achieved in 1974, when Bachall and Spitzer persuaded a panel of 23 members of the Greenstein Committee to back the following statement:

> In our view, Large Space Telescope has the leading priority among future new space science missions.

As scientific advances progressed, any technological doubts were put to rest by new advances in both science and engineering. Thus, what started out as a 'pie in the sky' venture gradually transformed LST into a 'glowing endorsement' for both scientists and US Congress members. So, in August 1974, the LST program successfully surmounted the planning phase to begin phase B of its operations, but other problems still beset the project.

NASA needed additional funding from other nations to make the space mission a technological reality. In particular, the European Space Research Organisation (ESRO) was consulted to provide one of the instruments and other pieces of hardware that would fly with LST. The Marshall Space Flight Center was chosen as the main NASA site where LST would be built at an estimated cost of $517 million to $715 million.

The labor in the design of LST was divided up into three sections by NASA officials: the Optical Tube Assembly (OTA), the

Scientific Instruments (SIs) and the Support System Module (SSM). NASA found two potential contractors for the optical tube assembly. The next phase of making LST a reality began in 1977, when contracts were awarded to Lockheed Martin for the SSM, and Perkin-Elmer for the telescope optics. Around the same time, NASA officials chose the following instruments to accompany the Space telescope on its maiden flight:

The Wide Field Planetary Camera (WFPC), with James Westphal as principal investigator.
The Faint Object Spectrograph (FOC), with Richard Harms of the University of California as principal investigator.
The High Speed Photometer (HSP), with Robert Bless of the University of Wisconsin acting as principal investigator.
The High Resolution Spectrograph (HRS), with John Brandt of the Goddard Space Flight Center as principal investigator.
And finally, the Faint Object Camera (FOC) built and supplied by ESA.

It was widely anticipated that LST could be brought back to Earth for upgrading and refurbishment instead of being serviced in orbit. The Space Shuttle program opened up the new possibility of maintenance and even the complete replacement of scientific instruments. This meant that the number of ground-based tests the payload instruments had to be subjected to could be reduced in order to reduce costs. Within a few years however, it became ever more apparent that the design of the Space Telescope had to be improved in order to minimize the number of repair trips needed by the Space Shuttle. This called for a revision of the program's cost and by 1980, the estimates for the entire program were between $700 and $800 million, with the anticipated launch date postponed until 1985. In private, many of the senior project managers assigned to the LST program suspected that the mission would be decommissioned by members of Congress.

Towards the end of 1982 more trouble met the LST program. PerkinElmer announced that their part in the LST was seriously underfunded and requested an additional $450 million to complete the telescope within the original schedule. Furthermore, the ambitious mission to launch LST suffered from poor management. These events impelled Samuel Keller, NASA's deputy associate administrator, to re-evaluate the entire LST program, concluding that the project was at least six months behind schedule and would need an additional $100 million to bring the LST to fruition.

What followed was a new and invigorated discussion with Congress that resulted in a larger budget of $1175 million, a 70 % increase in cost over the original budget plans! The launch date was changed to the end of 1986 by NASA. Moreover, the LST was renamed the Hubble Space Telescope (HST), after the American astronomer, Edwin Hubble (1889–1953), who discovered the expansion of the universe (see Box 1). Finally, while the original LST was designed to have an aperture of 3 meters, HST had to be reduced to just 2.4 meters (Fig. 2.2).

It was widely anticipated that the space telescope would be ready in time to assist Voyager 2's nearest approach to Uranus in 1986, as well as to observe Halley's Comet, during its perihelion passage a month later. But it was not to be. A considerable number of problems attended the American part of the program, so much so that it became incumbent upon senior NASA officials

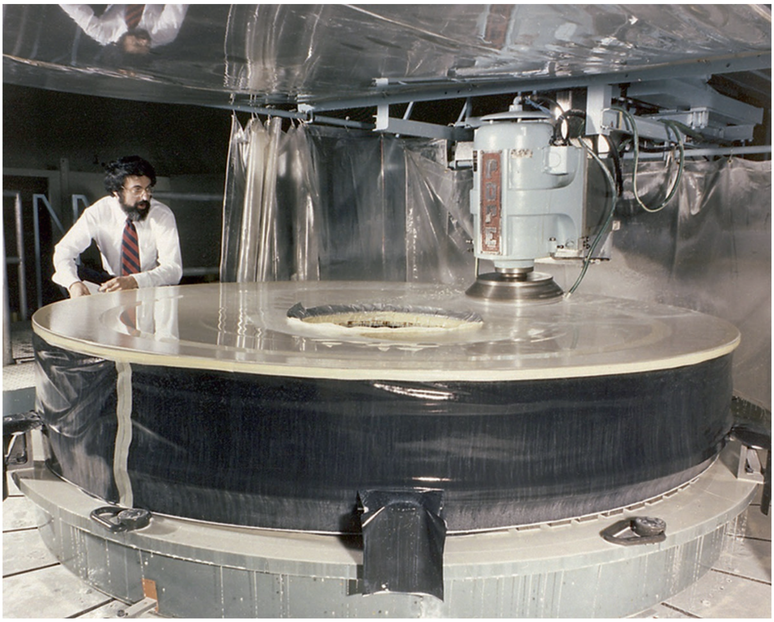

FIG. 2.2 HST's mirror blank being ground (Image credit: NASA)

to take a more active role in overseeing the HST project. Accordingly, a new project manager, John Welch, was appointed and NASA contracted BDM Corporation to undertake systems engineering of various components of HST's design. With a considerably enlarged budget, NASA made it a priority to greatly reduce the risk of the entire program by increasing both the number of spare components as well as the number of replacement units that could be placed in orbit. During this restructuring period, NASA finalized its commitment to undergo all repairs of HST from Earth orbit rather than bringing the telescope back down to Earth.

Though all parties redoubled their efforts to bring the project to fruition in the years following the 1983 hiatus, disaster struck. On January 28, 1986, the Space Shuttle Challenger exploded, putting the launch of HST on ice. In addition to this, a string of new problems were uncovered during the equipment testing under vacuum conditions. The cold (pun intended) reality was that HST would have missed its launch window anyway. Thus, a new launch date was set for November 1988, but even then, further delays in restoring the Shuttle Program meant that HST could not have been launched into space before 1990 (Fig. 2.3).

Fig. 2.3 Edwin P. Hubble (1889–1953), the famous American astronomer after which the Hubble Space telescope was named (Image credit: recherche-technologie.wallonie.be)

The Innards of HST

On April 24, 1990, after all setbacks had been resolved, the Hubble Space Telescope blasted off from Cape Canaveral on board the Space Shuttle. At launch, its total cost to NASA had skyrocketed to about $2000 million and $350 million to ESA. At the heart of the telescope was an f/24 Ritchey-Chretien reflector, with a primary mirror of 2.4-meter aperture (a little less than the 3-meter instrument originally planned) and weighing in at nearly one metric ton. In launch mode, the entire HST—sans its aperture door, solar panels, and antennae—had a length of 13.1 meters and was 4.4 meters in diameter, tipping the scales at 11.6 tons. The telescope was powered by solar panels with a power consumption of 2.8 kilowatts. It was placed in a 610 kilometer altitude orbit inclined at 28.8 degrees and had an anticipated minimum lifespan of 15 years. NASA's long-term plan was to include a refurbishing/ repair mission every three years by astronauts using the space shuttle.

Up until 1990, the largest ground based telescopes could achieve a resolution of 0.5 arc seconds (without adaptive optics) in the best seeing conditions, and about 1.0 arc seconds for about 2000 hours per year. The HST was expected to have a resolving power of about 0.1 arc seconds in the visible region of the EM spectrum and an impressive 0.015 arc seconds at ultraviolet wavelengths (121.6 nm). The amount of time that HST could engage in observations of the universe came to about 7000 hours per year. The telescope was expected to operate at UV, visible and near infrared wavelengths, covering wavebands from about 110 nm right up to 1.0 millimeter, giving it a far wider waveband range than any Earth-based telescope. This spectral range was not possible when HST was initially launched since the instrumentation capable of imaging at infrared wavelengths was not available when it first entered the vacuum of space.

Great advances in positioning technology meant that HST could undergo long-exposure imaging with a pointing accuracy of 0.01 arc seconds and remain within 0.007 arc seconds of that position for a full day! With such high resolution and exceptional pointing accuracy, it was expected that the telescope would be able to detect stars as faint as visual magnitude 27 after an exposure of just four hours. However, by extending the exposure time to 24 hours, objects as faint as magnitude 29 could be detected!

The Wide Field and Planetary Camera (WF/PC) placed on board HST was developed by engineers at JPL and consisted of eight CCDs arranged in two groups of four. The first CCD group was devoted to imaging in wide field mode (f/12.9) and the other arrays were used to image high resolution targets at f/30. The wide field CCD array had a 2.7 × 2.7 arc minute square field, made up of 1600 × 1600 pixels each covering an area of just 0.1 arc seconds. In contrast, the second planetary CCD of the WF/PC array was dedicated to imaging a much tinier field some 69 square seconds, with each of its 1600 × 1600 pixels covering just 0.043 arc seconds. The entire CCD array was cooled to a chilly −100 °C to optimize its signal-to-noise ratio. The individual pixels had to be coated with a special phosphor material called coronene to improve their efficiency in the UV region of the spectrum, as well as to enable a spectral range from 115 nm (UV) right up to 1.1 microns (infrared).

The Faint Object Camera (FOC), which was built by German firm Dornier Systems and commissioned by ESA, was fitted with an f/48 and f/96 camera system. The former had a field of view of 22 square arc seconds and came equipped with a variety of filters, prisms and diffraction gratings for high resolution spectroscopy. The f/96 camera was likewise designed to use polarizing filters and was also fitted with a special coronagraph to allow very faint objects to be imaged just one arc second away from another object up to 17 magnitudes brighter.

In the very highest resolution mode, which was necessarily confined to the ultraviolet region of the EM spectrum, the f/96 camera was transformed into an f/288 system that covered a field of view of just 4 arc seconds and a pixel size of 0.007 arc seconds. A team at British Aerospace designed the detectors for the FOC, which consisted of very high efficiency photomultipliers. These in turn were coupled to television cameras that, remarkably, could detect a single photon of light! In addition, the full 1024 × 1024 pixel could be processed in either 8-bit or 16-bit mode.

Two other instruments coupled to HST included the Faint Object Spectrograph (FOS) and High Resolution Spectrograph (HRS) both of which were fitted with an array of diodes to measure radiation intensities at various wavelengths of the spectrum. HRS was designed and constructed by Ball Aerospace and could produce both medium and high resolution ultraviolet spectra of stars as faint as magnitude 19. Martin Marietta designed the FOS, which was able to capture spectra of significantly fainter stars with magnitude as low as 22.

The High Speed Photometer (HSP), the simplest and cheapest of HST's on-board instruments, was designed by a team of engineers based at the University of Wisconsin and, remarkably, contained no moving parts. This extraordinary instrument was capable of detecting minute changes in brightness in objects as faint as magnitude +24 and with a time resolution of just 0.0.016 milliseconds.

Over the first few days, after arriving in its assigned orbit, HST opened up its solar panels and deployed its high gain antenna. The cargo bay of the Shuttle was then slowly opened and the famous telescope carefully coaxed into position. Yet even at this stage, a few technical hitches delayed the telescope from seeing first light until May 20. With a sense of great anticipation, HST's first target was the open cluster NGC 3532, which also contained a double star with angular separation of just one arc second. The double was clearly resolved although, puzzlingly, the two stars were not clearly defined points of light. And while some NASA officials were visibly relieved, others immediately suspected that there was something awry with the images.

On the next evening, Roger Lynds of the NOAO and a member of the WF/PC team boldly suggested that the HST had a pretty bad dose of spherical aberration. Chris Burrows, an optics expert with ESA, agreed with Lynds, adding that as well as spherical aberration, the telescope images were showing significant levels of coma. After attempting a few clever maneuvers, like moving the primary mirror towards the secondary or using the actuators to change the shape of the mirror ever so slightly, the images could still not be improved. When the first images from the FOC were processed, images showed exactly the same effect. Over the next couple of days, engineers realized that the spherical aberration showing up in HST's image could not be fixed using hardware on board HST (Fig. 2.4).

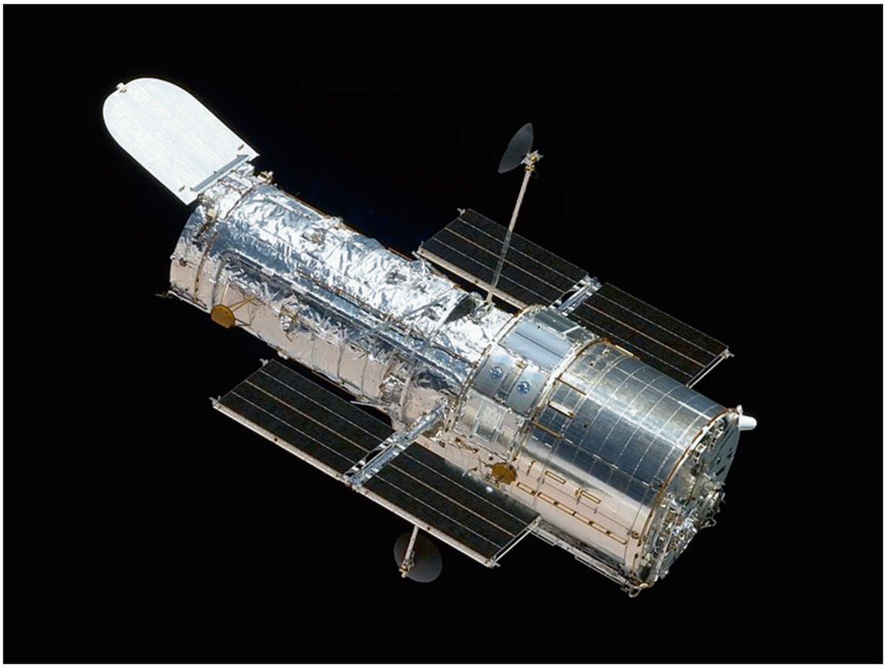

Fig. 2.4 HST in orbit above the Earth (Image credit: NASA)

On June 27, 1990, Ed Weiler, the chief scientist with the HST program, was given the unenviable task of announcing to a room full of curious journalists that the newly launched $1.5 billion observatory's supposedly flawless 2.4 meter primary mirror was misshapen because it was ground to the wrong shape, and so was unable to bring starlight to a crisp focus. In theory, the mirror ought to have brought 70 % of the light incident upon it to the same focal point, but HST could only manage a paltry 10 to 15 %.

Moving from the center to its edges, the mirror was discovered to be too shallow by about 2 microns. In and of itself, this was only a tiny fraction of the width of a human hair, but it was enough to destroy the definition of the famous space telescope. From an optical standpoint, the parabolic shape of the mirror was wrong! This tiny imperfection made NASA's greatest telescope the butt of jokes all over the world and the subject of great consternation on Capitol Hill.

After a long and protracted investigation by officials, the root cause of the calamity was elucidated. A technician had inadvertently inserted a small 3 mm diameter washer into a device called a null corrector, an instrument employed to check the mirror's shape during its production a few years earlier. In retrospect, there were telltale signs that something was wrong during the mirror testing phase of project, but these were completely ignored. What is more, performing a thorough optical test on the primary mirror was not undertaken because of efforts to minimize costs. In addition, it was decided that performing these tests would compromise the cleanliness of the telescope. Skipping added testing would thus reduce the risk of biological contamination.

Understandably, Weiler was totally devastated by the findings. "If you had polled all the engineers and scientists at Cape Canaveral the night before the launch for the top ten concerns they had," he said, "what could break on Hubble or what wouldn't work on Hubble, I would bet my house and a lot more that not one of them would put on their list the mirror's wrong shape and we've got spherical aberration. Nobody worried about that because we were assured by the optics guys that we had the most perfect mirror ever ground by humans on Earth."

Remarkably though, the misshapen HST primary mirror was still used to undergo some cutting edge science. One of the most ambitious goals of the astronomical community was that HST would be capable of imaging planets orbiting their parent stars via the Faint Object Camera (FOC). Unfortunately, the defect to Hubble's mirror precluded the use of its coronagraph, so these exoplanets couldn't be detected. Significantly though, the hobbled HST could still be used to image the gas and dust clouds surrounding young stars such as Vega and Beta Pictoris—with the aim of following up earlier work conducted by the Infrared Astronomical Satellite (IRAS). In 1991, a team of astronomers led by Albert Boggess of the Goddard Space Science Center employed the High Resolution Spectrograph to examine the spectrum of Beta Pictoris at UV wavelengths. These studies demonstrated that the gas present in the dust cloud was moving inwards towards the star at speeds on the order of 50 kilometers per second. The same team also uncovered clumps of gas that many now think are new planets in the process of forming (Fig. 2.5).

Throughout the summer months of 1990, NASA engineers precisely mapped the shape of HST's mirror, discovering it had

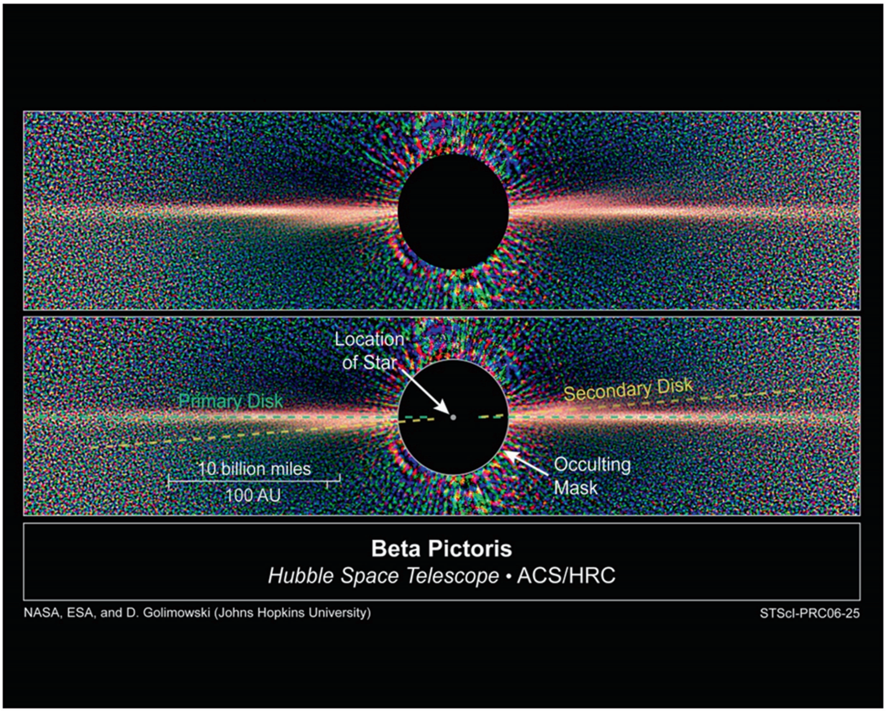

Fig. 2.5 HST images of the dusty disk surrounding the star Beta Pictoris (Image credit: NASA)

been ground just as perfectly as advertised but to precisely the wrong shape! While this investigative work was going on, NASA engineers picked their brains in order to arrive at possible fixes. These included everything from sending an astronaut crew to HST to replace the secondary mirror with another one, installing a circular diaphragm around the periphery of the tube, thereby reducing the aperture and improving the focus by blocking out the outer regions of the primary mirror which had the greatest defect. Before all that happened however, NASA had to 'officially' offer an admission that the telescope mirror was misshapen, and it was incumbent upon Weiler to make that announcement.

When the whole world was aware of HST's problem, it was the NASA optics experts' responsibility to arrive at a workable solution to the problem. It was John Trauger, the principal investigator with the WF/PC, who first suggested a way around the problem. Analyzing the images from HST, optical engineers employed a computer assisted method known as deconvolution to design 'corrective glasses' with a prescription that introduced aberrations that were exactly the opposite in sign from those ground into the mirror. By a stroke of good fortune, an exact replica of the WF/PC that was built several years earlier could be called into service to provide that correction. But that would only work if a set of small and carefully designed mirrors were positioned in front of the original Hubble instrument, the Corrective Optics Space Telescope Axial Replacement (COSTAR).

In August 1990, the FOC was instructed to carry out a 28 minute exposure of SN 1987A, the supernova remnant located in the Large Magellanic Cloud, at a specific wavelength corresponding to the line of doubly ionized oxygen (OIII) at 500.7 nm. Such an exposure showed that the star was surrounded by an enormous egg-shaped structure measured to be about 1.6 arc seconds across. Initially, it was thought that this structure was just a ring of material that must have been ejected by the exploding star at some time in the past, and inclined at 43 degrees to our line of sight. The ring was set alight after it was irradiated with UV light some 240 days after the explosion. This meant that sometime between 1999 and 2002, the material from the supernova explosion was predicted to collide with the ring debris. What's more, these observations enabled astronomers to increase the accuracy of the distance to the LMC (which is now measured at 169,000 light years with an error margin of just 8000 light years).

The enormous light grasp and resolving power of HST allowed astronomer Francesco Paresce, based at the Space Telescope Science Institute (STSc1), to peer deep into the center of the bright globular cluster 47 Tucanae. By nulling the light from the predominant red giant stars, the team found twenty one so-called 'blue stragglers' in regions close to the core of the cluster, which suggested that some stars must have come so close to each other within the dense cluster that they coalesced with each other in some sort of violent merger. Before these observations were made, it had been widely and commonly accepted that all globular clusters were of roughly the same age. But if blue stragglers had been produced either by stellar mergers or by some kind of mass transfer process, some of the globular clusters were being rejuvenated, even if they were strictly the same age as their red giant companions. Thus, the color of a star is not an absolute indicator of the age of stars in a cluster.

In 1991, Lowell Observatory astronomer, Jon Holtzman, and colleagues, utilized the WF/PC 1 to image the central region of the elliptical galaxy NGC 1275 at the heart of the Perseus galaxy cluster, finding what appeared to be about 50 blue colored globular clusters that were estimated to be only about 300 million years old. This was a very surprising discovery, which could only be explained if several fairly recent galaxy mergers took place to create NGC 1275. Globular clusters are not necessarily the 'old men' of the galaxy and could have formed much later in the evolution of the Milky Way Galaxy and other galaxies. In other galactic work, astronomers turned HST toward the active radio galaxy M87, which was thought to harbor a supermassive black hole at its epicenter.

As we have seen, more than 1000 astronomers used HST to gather images even in its flawed state but had to rely heavily on computer processing techniques to glean the best from the beleaguered orbiting observatory. But this was no panacea compared to going up and fixing the optics.

When John Trauger (JPL, Pasadena, California) learned that the optical problem had been traced to a misshapen mirror, he immediately saw a partial solution. Since 1985 he and his colleagues had been building a backup for Hubble's main scientific instruments, the Wide Field and Planetary Camera (WFPC) and it could easily be modified to negate the effect of the telescope's aberration.

Like the first one, the second camera would contain eight small Cassegrain reflectors. These relayed the f/24 beam from the telescope to a sensitive CCD camera, which changed the image scale to f/12.9 for the four wide field chips and to f/28.3 for the purpose of high-resolution planetary imaging. Trauger realized that the Cassegrains' dime-sized secondary mirrors could be given an amount of spherical aberration equal in magnitude but opposite in sign to the Hubble's, thereby bouncing corrected images to the CCDs.

Before new relay secondaries could be manufactured, scientists had to determine the right prescription. They did this in two ways; by studying actual images from both cameras and by examining the fault test device that caused the spherical aberration in the first place. The results agreed by more than 5 %.

HST's primary mirror was about 2 microns too flat at the edge, so the corrective optics had to be higher at the edge by the same amount. Since these mirrors were only a centimeter in diameter, it followed that they had to be very steeply curved. That said, achieving this figure was fairly easy to achieve. What Trauger and his colleagues could not foresee, and what turned out to be a much more challenging problem, was the task of aligning the optical components in such a way as to provide diffraction limited performance even in the presence of spherical aberration.

If the telescope and camera were incorrectly collimated by as little as 2 % of the relay mirror's diameter, then coma would have become the predominant optical aberration and HST would have produced even worse images than before. The existing latches and rails that positioned the camera in the telescope were simply not rigid enough to provide the level of alignment tolerance needed. So, Trauger and his associates were left with no better option than to adjust the camera's new optics in orbit. Such a project added to the expense of the mission so something else had to go.

After considerable reflection and deliberation, the team decided to remove four of the eight CCD channels. This meant that it could no longer alternate between two-by-two mosaics of f/12.9 (wide field) and f/28.3 (planetary) detectors. In contrast, the new camera could produce a single mosaic image comprised of an L-shaped trio of wide-field images as well as a smaller, high-resolution image sampled in the corner of the CCD array.

The pickoff mirror that directed the light from the telescope into the camera was now fully steerable, as were the fold mirrors that lined up the beams with the relay Cassegrains. The mirrors were positioned on three ceramic actuators, the heights of which could be lengthened or shortened by a few microns when a small voltage was set up across them. In this way, adjustments could be made to ensure that the alignment was spot on.

Despite the loss of half its CCD detectors, the new camera was significantly more sensitive than the old one, allowing shorter exposures to be made. WFPC-2 was an improvement on its predecessor in other significant ways too, like its ability to offer better performance at ultraviolet wavelengths. Trauger was satisfied that these innovations would bring HST's capabilities in line with what astronomers would be happy with.

Astronomers and NASA were understandably excited by the easy fix available through WFPC-2, but many still expressed concerned about the fate of Hubble's other instruments, none of which had planned replacements. To address this issue, Riccardo Giacconi, the director of STSc1 at the time, appointed a "strategy panel" of astronomers, optical engineers, and astronauts in August 1990 to explore strategies that could be adopted to fix the Faint Object Camera (FOC), the Goddard High Resolution Spectrograph, the Faint Object Spectrograph and the High Speed Photometer on board the orbiting observatory.

The panel aimed to establish a practical method that would fit into a program dedicated to the telescope's maintenance and servicing schedule. Murk Bottema of Ball Aerospace first suggested using mirrors similar to the WFPC-2 relay secondaries. Because they absorb UV radiation, ordinary glass lenses simply wouldn't have worked. To counter this, Bottema's idea involved the use of two mirrors working in concert to correct the aberration beam entering each of the scientific instruments. The first mirror would intercept light from a convenient spot in the telescope's field and direct it to a second mirror, which would cancel out the aberration before directing a corrected beam into the instrument.

Around the same time, Crocker discovered a way to direct the mirror images to the right places in the focal plane. During the development phase of HST, a 'dummy' scientific instrument was set up for testing. Consisting of little more than an empty box, the Space Telescope Axial replacement (STAR) could be substituted for any of the phone booth-sized instruments that were mounted parallel to the telescope's optical axis (that is, all instruments but the WFPC). Crocker suggested the removal of one of these instruments and the insertion of a modified STAR to house Bottema's Corrective Optics STAR (COSTAR).

The same panel of experts recommended that COSTAR replace the HIGH SPEED Photometer (HSP), which was Hubble's least used instrument. HSP team leader Robert Bless (University of Wisconsin) initially planned to include a miniature HSP made from spare parts with COSTAR. In the end, engineers assigned to COSTAR could not find a suitable light path to enable such a device to operate. Ball Aerospace completed COSTAR in two years and four months. The 290-kilogram marvel of technology contained five mirror pairs—two each for the FOS, FOC and one for the Goddard spectrograph, whose two apertures were close together. These mirrors had apertures in the range of 12 to 25 mm, some of which had steeply curved spherical surfaces to provide the necessary optical correction. As with WFPC-2, optical alignment had to be very precise, so provision had to be made to enable flight controllers to adjust each Mirror 1 in such a way as to aim it squarely at Mirror 2. All ten mirrors were installed on COSTAR and mounted on a sophisticated optical bench. A veritable marvel of miniaturization, the device was actuated using 12 tiny DC motors with ten mirrors, four arms, and innumerable sensors and connecting wires compacted into a space the size of a shoebox.

The installation of COSTAR ensured that Hubble's image quality would be good enough to concentrate 60 % of a star's light inside a radius 0.1 arc seconds, making it almost as good as the original 70 % aimed for by NASA. COSTAR wasn't perfect however. It increased the focal ratio (or magnification) of each of the corrected beams, and in so doing reduced the apparent field of view of the image. For example, the original f/48 and f/96 operational modes of the FOC now became f/75 and f/151, respectively. What is more, the two additional reflections reduced the amount of light reaching the instruments. In particular, the combined reflectivity of Mirrors 1 and 2 meant that only about 80 % of visible light and 60 % for ultraviolet light could be captured.

When HST's optical glitch was first uncovered, the pertinent question on everyone's mind was; why wasn't it remedied before it was launched? NASA could not afford to make the same mistake twice and so had WFPC-2 and COSTAR thoroughly checked over and over again, in different ways, in order to ensure that would both fit in the telescope as planned and perform as intended.

Remarkable though it may seem, the optical aberrations of HST were not the first problem to beset the famous orbiting observatory. From the outset of its days in orbit, the great telescope had vibrated violently as it traversed the day-night terminator. After careful study, engineers determined that the origin of these vibrations arose as a result of the spacecraft's twin solar cell arrays. Apparently, the giant panels (each 12 meters long and 2.8 meters wide) began to flap in response to the rapid heating or cooling that attended each terminator crossing, resulting in a noticeable jitter in the telescope's pointing that occurred for 5 or 10 minutes. Usually when the solar cells were quiet, the tracking sensors locked onto suitable guide stars with a precision better than 0.005 arc seconds which actually exceeded NASA's anticipated pointing accuracy (0.007 arc seconds). But once the jittering started, the telescope would be knocked off target, disrupting the intended observation and the recording of precious data. Indeed, throughout HST's first year in orbit, all observations that occurred during terminator passages had to be cancelled and re-scheduled. Eventually though, NASA flight controllers gained sufficient understanding of these vibrations to reprogram the HST's onboard computer and eliminate the disruptions by making slight adjustments to the rotation speeds of onboard flywheels.

After these bugs were ironed out, the telescope hardly ever lost its ability to lock onto targets. However, the much-increased complexity of the jitter reduction software cut into the already limited amount of computer memory available for data retrieval and analysis. More alarming still was the prospect that the persistent flapping of the solar panels would eventually cause mechanical stress (such as metal fatigue) in the booms that held the arrays together on the telescope. For example, if one of them were to pry itself from the body of the telescope, it would quickly drain the electrical power and cause the whole spacecraft to shut down. As luck would have it, the company that built the solar arrays, British Aerospace, had already been working on a spare set of panels as soon as this problem came to light. These new panels were planned to be installed in the mid to late 1990s, by which time the power output on the original panels would have degraded considerably owing to overexposure to the deadly environment of outer space. This time however, the new arrays were to be given additional thermal protection, and their construction was sped up so that they would be completed in time for the greatly anticipated 1993 shuttle repair mission.

The solar cells were arranged in blanket-like layers that could be extruded in opposite directions from a drum, and made to move along by thin rods called BiSTEMs. Constructed from two flexible, semiconductor ribbons, they slid together as they were extended from their storage cassettes, similar to an ordinary household tape measure. The blanket ends were affixed to a bar placed between the two BiSTEMs. The project manager at British Aerospace, Michael Newns, figured out that these BiSTEMs, as well as the drum and the attachment between the blankets and bar, had all contributed to the heat-induced jitter, since each would have the potential to stick or suddenly become free to slip as the temperature alternated between hot and cold. The improvements that were built into these new arrays consisted of bellows fashioned from aluminized Teflon that were used to insulate the BiSTEMs, a braking system for the drum, and an attachment mechanism for the blankets.

While the Shuttle mission prioritized correcting the telescope optics and the jitter of the solar array, a potentially more serious threat came to the fore. Three of HST's six gyroscopes failed, leaving a key component of the pointing-control system without any replacements. These gyroscopes were designed to sense the telescope's turning rate, three of which were necessary to calibrate the motions around HST's three axes. The gyroscopes were packaged in pairs inside three rate-sensing units (RSUs), each an associated electronics control unit (ECU) to regulate them.

In a lucky twist of fate, one gyroscope had failed in each of the three RSUs so the telescope continued to operate. Two of these shut downs had already been linked to faulty RSU circuitry. However, two of the gyroscopes that remained operational utilized the same circuitry. The third and final failure apparently occurred when a fuse blew elsewhere in the gyro power system, shutting down the ECUs as a result. So the replacement of two RSUs and two ECUs, together with an upgrade to more sophisticated circuit breakers, would leave HST with six operational gyroscopes.

Even if HST had perfect optics and rock stable solar panels, NASA would still have to dispatch a repair mission to replace any malfunctioning gyros to allow the telescope to continue making observations of scientific value. It might have been possible to control HST using a pair of gyroscopes, magnetometers and sun sensors, but this couldn't happen without upgrading the software controlling the telescope's moment-to-moment operation. Any such upgrading was beyond the remit of the repair time leading up to the planned launch date. Addressing a team of astronomers, servicing program manager, Kenneth W. Ledbetter, after calling attention to this precarious situation quipped, "If you know any gyro heath chants, now would be a good time to say them!"

HST was not without its fair share of electronic problems. Two out of the six memory modules installed in the spacecraft's main computer had malfunctioned, as did the prime unit which oversaw the exact positioning of the solar cell arrays. What is more, the Goddard spectrograph with its low voltage power supply, an image intensifier in the Faint Object Camera and both magnetometers started to behave erratically and even failed to work on some occasions. After some investigation, the cause was found to be broken solder connections and/or failed components.

To repair the main computer, the astronauts were forced to include a co-processor module with a great deal of additional memory. If that failed, however, repairs would take considerably longer and would overstretch an already cramped space-walk schedule. In addition to the co-processor module, HST would get new and improved solar-array drive electronics, as well as a relay box to circumvent the spectrograph's balky power supply. New magnetometers would also be installed during the repair mission.

Three space walks were planned for the Hubble repair mission scheduled for January 1993. However, the number of problems continued to mount for the famous space telescope, resulting in further launch delays due to needed repairs. By March of 1993, the number of space walks increased from three to four, then to five in June. At that point, the Space Shuttle Endeavour, which became the newest member of NASA's fleet, was the only orbiter capable of making the flight, as it alone could carry the prerequisite amount of fuel, air and water to successfully carry off the mission.

All the sophisticated cargo required for the repair mission had been delivered to NASA by late August 1993, and some had even been dispatched to Cape Canaveral for incorporation into the payload bay of Endeavour. NASA had divided the cargo into two main classes. The primary payload consisted of COSTAR, WFPC 2, new solar panels, gyro pairs with fuses and their attendant electronics, a magnetometer and the electronics that ran the solar panels.

The Secondary items were designed to improve HST's scientific capabilities, and included the Goddard spectrograph repair kit, the computer co-processor to reduce the changes of failure, another magnetometer and a second set of gyro electronics. Planning the sequence of events that would successfully restore HST to good working order was no easy task and, inevitably, had to include compromises between payload priorities and the time available for each spacewalk. It was all a massive exercise in risk assessment. Reviewing the scientific literature of the day, the pressure on NASA to deliver in the aftermath of the fiasco was palpable to say the least!

The all-important COSTAR apparatus, designed and built by Ball Aerospace over the course of three years, together with WF/PC 2, were both ready to be included on the first anticipated HST servicing mission, which was pushed forward to December 1993. In the hours leading up to the spacewalk to rejuvenate a myopic Hubble, a 50-strong army of astronomers and engineers nervously congregated around a large television screen as that first picture was downloaded for analysis. "That was the first moment I knew we had fixed it," Weiler recalled. "The first picture had a star right in the center. It was only that star, but it was crystal sharp clear and the crowd went crazy! I thought the then NASA Administrator, Dan Goldin, was going to fire me the next day but instead, he congratulated me."

NASA was understandably reserved about releasing the first light results of the most famous servicing mission in history, deciding instead to collate more data that would silence a skeptical press and public, demonstrating once and for all that the most expensive telescope in the history of the world was worth every dime lavished upon it. So, slowly but surely, over the Christmas period of 1993 and extending into the first few days of January 1994, about a dozen new images from HST were carefully analyzed by mission scientists (Fig. 2.6).

NASA finally arranged a press conference at Goddard on January 13, 1994, which coincided with an American Astronomical Society meeting in nearby Washington. The conference even attracted the attention of Barbara Mikulski, Maryland senator, who was shown the 'before' and 'after' images at first hand. "My god," she exclaimed, "it's like putting my glasses on!"

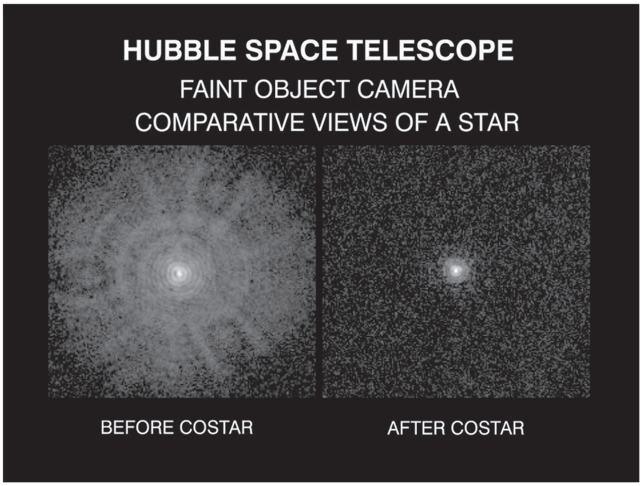

Fig. 2.6 Showing a star image obtained before and after the servicing mission (Image credit: NASA)

So, in the end, the $50 million COSTAR as well as the $23.9 million WF/PC 2 upgrade saved HST from becoming the great big techno turkey in the sky the press wanted it to be. But soon, HST's intrepid mission was ready to push the envelope out on our knowledge of the universe, as well as our place within it. This will be the subject of the next chapter.

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