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A STUDY OF HUBBLE SPACE TELESCOPE OPERATIONS

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▲ The Advanced Camera for Surveys (ACS) instrument aboard the Hubble Space Telescope captured this view of the Orion Nebula in 2006. (NASA/ESA/M. Robberto [STScI/ESI]/HST Orion Treasury Project Team: heic0601a)

FOREWORD

▲ Image of NGC 2174, the Monkey Head Nebula, taken by Hubble's Wide Field Camera 3 in 2014. (NASA/ESA/Hubble Heritage Team [STScI/AURA]: heic1406a)

▲ Major General Charles F. Bolden, Jr., NASA Administrator 2009–2017. (NASA: 200907290001HQ)

by Charles F. Bolden, Jr.
NASA Administrator, 2009–2017

One of the highlights of my career at NASA was helping deploy the Hubble Space Telescope (HST) from the payload bay of the Space Shuttle Discovery on 25 April 1990, and watching Hubble begin its amazing decades exploring the universe from Earth orbit.

As pilot of the STS-31 mission, I spent much of that day at the aft station on Discovery's flight deck. There, I helped mission commander Loren Shriver fly the Shuttle and helped remote manipulator system (RMS) operator Steve Hawley lift HST out of the payload bay. As I read out position numbers to Steve and monitored Hubble's movements, Steve discovered that the robotic arm in space did not behave in the same way as the arm in the simulator on Earth. Steve had almost no room for error—there was barely enough room to fit my fist into the space between HST and the side of the payload bay—and so he had to spend nearly an hour more than expected slowly and gently moving the gigantic Hubble out of the payload bay by moving one joint of the RMS at a time.

Once HST was safely above the payload bay but still in the grasp of the robotic arm, we deployed Hubble's two antennas and the first of its two large solar arrays. The second solar array failed to fully deploy, and we worried about the limited battery time on HST running out before the solar array could deploy.

The decision was made that our other two crewmembers, Kathy Sullivan and (the late) Bruce McCandless, should get into their spacesuits and get ready to go outside and help deploy the solar array. I immediately went down to the middeck to assist Bruce and Kathy donning their extravehicular mobility unit (EMU) spacesuits and move into the airlock.

As we depressurized the airlock, we got word from Mission Control of a possible solution to the solar array problem. The HST control team at Goddard Space Flight Center transmitted a command that bypassed a software module in the telescope designed to protect the arrays from excessive tension that could damage an array. When a new deploy command was sent, the array opened properly. Loren maneuvered Discovery into the proper deploy attitude, Steve released HST from the robotic arm, and Loren moved the Shuttle away from Hubble, completing the deployment as I photographed the scene.

The moment was bittersweet because Bruce and Kathy, who may have had more time with Hubble than any other people on the planet, were still inside the airlock and missed the historic moment of deployment. At that time, no one in the astronaut office had done more work to prepare for this moment than Bruce and Kathy. My two crewmates had also helped devise tools and procedures to deploy and service HST. They had seen to it that Hubble was fitted with handholds and grapple fixtures, and their work paid off years later when it came time to service and repair HST on future missions.

Most of our crew had been named to the HST deployment mission nearly five years before we actually flew, so we had plenty of time to prepare, think, and talk about Hubble. We all agreed that Hubble would revolutionize astronomy and astrophysics, but looking back, I now realize that none of us had any idea of what a game changer it would be.

Our crew had even flown to England to visit the British Aerospace plant where HST's solar arrays were being built, but we did not realize how useful that trip would be for our deployment mission. Although we had thought about contingencies we might face, we didn't yet know how important Shuttle servicing missions would be to carrying on the work of the Hubble Space Telescope.

After we returned home from STS-31, I hoped to get another flight to HST. That didn't happen, but more than two decades later, after I had flown twice more to space and then wrapped up my career in the U.S. Marine Corps, Hubble returned to my life.

That came in 2004, after the tragic loss of the Space Shuttle Columbia and the crew of STS-107 caused NASA Administrator Sean O'Keefe to cancel the fifth and final HST servicing mission. I was asked to join a high-level committee of the National Academies reviewing options for extending the life of HST. Our committee concluded that proposals to service HST using robotic spacecraft were not yet viable, and so we recommended that NASA permit another crewed servicing mission with additional safety measures.

That servicing mission (STS-125) ultimately flew in 2009, just weeks before I became Administrator of NASA. The mission's outstanding success meant that I never had to make a difficult decision about Hubble, but I had the pleasure of taking part in celebrations of its 20th and 25th anniversaries on orbit.

As HST reaches its 30th year in space with an amazing record of accomplishment, I thank all the people from all parts of NASA that have made these scientific achievements possible. That includes the people of Marshall Space Flight Center in Huntsville, Alabama, who supervised the building of HST; the people of Goddard Space Flight Center in Greenbelt, Maryland, who control Hubble and created the tools and techniques to repair it; the people of Johnson Space Center in Houston, Texas, where astronauts like me prepared for Shuttle servicing missions and where those missions were controlled; and the people of Kennedy Space Center in Florida, where Shuttles and their cargos, including HST and its replacement instruments, were prepared for flight and launched.

Our partners in the European Space Agency (ESA) have played a major role in HST in the form of solar panels, the Faint Object Camera, and scientists who made outsized contributions to Hubble's research findings.

Many contractors helped make HST a reality, including the Space Telescope Science Institute, which organizes HST's scientific work, and Lockheed Martin, which built Hubble and continues supporting the maintenance and control of HST.

Hubble's reach extends around the world because observing time on the telescope and its archives are open to anyone on Earth. Scientists from every part of the world and even a few amateur astronomers have been granted observing time on the Hubble Space Telescope. Larger numbers of people have used data from HST for their research projects.

As I write these words, Hubble and its instruments continue to provide world-leading science to the astronomers and astrophysicists around the world. With its five instruments and its Fine Guidance Sensors (FGS) also providing observations, Hubble is far more than a telescope—it's a fully equipped observatory.

Hubble has looked back most of the way to the early days of the universe, and we anticipate deeper views into the past with the James Webb Space Telescope.

This book, which examines HST's first three decades of operation, fulfills another NASA commitment, this one to disseminate our findings as widely as possible. We have learned many lessons from Hubble that are best explained through histories such as this book. I hope it will help more people appreciate the phenomenal work done by the people of NASA, our partners at ESA, and our contractors, to make Hubble the gigantic success it has become.

▲ The Bubble Nebula, or NGC 7635, was crafted from Wide Field Camera 3 images in 2016.
(NASA/ESA/Hubble Heritage Team [STScI/AURA]: STScI-2016-13)

… 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…

—Lyman Spitzer, Jr., 1946

The most important discoveries will provide answers to questions that we do not yet know how to ask and will concern objects we have not yet imagined.

—John N. Bahcall, 1990[1]

The launch of the Hubble Space Telescope in 1990 began a lengthy period of scientific work in space that has reached 30 years and is continuing as this study is being completed. First and foremost, this book tells the story of HST operations during that time. That story is much bigger than HST itself. Hubble is a project of the National Aeronautics and Space Administration and the European Space Agency, and it also involves many private contractors, universities, and individuals. In addition to the space telescope itself, HST operations depended on NASA control centers on the ground, facilities where astronauts and others prepared deployment and servicing missions for HST using the Space Shuttle, a scientific institute that was created to serve scientists from many nations who have made observations with HST, and European Space Agency facilities. All of these facilities and institutions have evolved during HST's time on orbit.

The Hubble Space Telescope is almost unique amongst NASA programs and spacecraft in terms of its longevity. Spacecraft such as the two Voyagers have operated longer than HST, but their primary missions were completed roughly 12 years after they were launched. The Chandra Space Telescope was launched nine years after HST and is still operating. The International Space Station has been on orbit for more than 20 years. HST has been carrying out its primary mission for 30 years and counting, thanks to five maintenance, repair, and replacement missions involving the Shuttle and its astronauts that have increased Hubble's capabilities over its lifespan. The last Shuttle servicing mission to Hubble took place in 2009, less than 20 years after HST was launched. Hubble has continued to operate without benefit of on-orbit servicing for more than a decade.

HST is still transmitting images and data to the ground for the use of scientists and, in some cases, the appreciation of the public, and there is a good prospect that it will continue to do so for years to come. Even after Hubble completes its final observation, it will still be far too early to properly assess the impact and importance of HST's scientific bounty, since many of its observations are going straight to archives where they may remain for years before they are used and their importance realized. Because Hubble is still actively exploring the universe, this book should be considered an early draft of history that discusses some events that took place decades ago and some that occurred as research and writing was going on.

NASA has statutory responsibility to "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."[2] From its beginnings, NASA has included the study of history and historians within the meaning of this responsibility, centered in the NASA History Division at Headquarters. NASA has supported the creation of many quality books, monographs, and chronologies on its programs, and it maintains archives that relate to its work. NASA has assisted in historical work on HST that began long before it was launched in 1990, and the best-known product of this support was Robert W. Smith's 1989 book on how HST was transformed from an idea to a fully built space telescope ready for launch into space, *The Space Telescope: A Study of NASA, Science, Technology, and Politics*. That book remains the outstanding study of how HST was created and is noteworthy for its exploration of the interplay between scientists, engineers, politicians, and industrialists that shaped the Hubble Space Telescope and brought it to the launch pad in 1990 as a prime example of what has become known as Big Science.[3]

In 2014, nearly a quarter century after HST was launched, Goddard Space Flight Center issued a request for proposals to create a history of HST operations, along with an archive of documents and interviews with program participants to support this and future historical studies. I began research work on this book later that year. The idea behind starting this study while Hubble was still operating was the reality that many participants in the early phases of the program were leaving the scene and some source documents were becoming more difficult to find. My work on this book has benefitted from strong support from NASA personnel at Goddard and the NASA History Division, which has agreed to publish this study. The work that led to this book has also been assisted by personnel from other NASA Centers, the Space Telescope Science Institute, and other NASA contractors, along with scientists who have used observing time and data from HST.

To understand HST operations, chapter one examines the events that brought HST to the launch pad in 1990. It is important to look back to how the ideas of space exploration and space astronomy led both to the Hubble Space Telescope and to the Space Shuttle that carried HST into space and then was used to mount servicing missions to it. Not all astronomers embraced the idea of HST, and its promoters had to work hard to win approval for the space telescope in the straitened economic circumstances of the 1970s. The HST program was often under managerial and financial stress that underlaid the error that was introduced into HST's main mirror while it was being ground and polished. The defect in the mirror forms the heart of the story of HST's first four years on orbit, which is outlined in chapters two and three, as scientists and engineers learned and absorbed what had happened to the mirror and then created and implemented solutions to the defect, known as spherical aberration, that resulted from the mirror's incorrect shape.

Once the mirror problem was overcome during the first Shuttle servicing mission in December 1993, HST quickly became one of NASA's signature programs, thanks to the images it has obtained of objects as close as the Moon and as far away as galaxies billions of light-years distant. As HST began operations, millions of people equipped with newly created personal computers tied together on a newly expanded computer network known as the internet acquired new ways of collecting images and other data from HST. Scientists have also gained undreamed-of online access to Hubble data thanks to these new means of communications. Chapter four examines HST's place in the advent of cyberspace and the power of its images in publicizing and promoting astronomy.

HST is unique among robotic spacecraft because it was serviced, repaired, and upgraded five times by Shuttle astronauts during its first 20 years on orbit. All of those servicing missions involved NASA's Space Shuttle training and launch facilities, along with the contractors who built the instruments, tools, and other equipment needed for these flights. Scientists who use HST played a major role in selecting and creating the instruments that were installed on

Hubble during those servicing missions. Each of these servicing missions had its own goals and its own history, which are related in this book. The stories of the second, third, and fourth servicing missions are recounted in chapter five.

As an observatory using the most powerful telescope launched into space at that time and a variety of instruments to image, measure, and analyze distant objects, Hubble has made a major impact on our understanding of the universe. Chapter six takes a preliminary look at HST's scientific output, starting with an examination of how teams of astronomers are using HST and other telescopes to determine the size and age of the universe with greater precision than ever before. These measurements led to the surprising discovery that the universe is expanding at an accelerating rate, which opened new questions about what the universe is made of. A series of "Hubble Deep Field" images has looked back to the early days of the universe. Other HST scientific advances include supermassive black holes in the centers of galaxies, views of the birth and death of stars, views of planets orbiting other stars, and tracking of weather on planets in our own solar system.

After the fourth Shuttle servicing mission visited HST in 2002, astronomers hoped to see Hubble's life extended well beyond its originally planned 15 years with one more servicing mission and hopes for another. But less than a year later, the loss of the Space Shuttle Columbia and its crew put the future of the Shuttle Program into question. By early 2004, NASA Administrator Sean O'Keefe had decided to cancel the fifth HST servicing mission, setting off an unexpectedly large controversy amongst astronomers and the public about the future of HST. Chapter seven outlines these events and the subsequent decision made by O'Keefe's successor Michael Griffin to proceed with the mission, which turned out to be a great success that has added more than a decade of life to HST.

Chapter eight focuses on the infrastructure back on Earth that supports HST and how it has evolved over the three decades of HST operations. The control facilities at Goddard and the scientific work of the Space Telescope Science Institute (STScI) began with preparations for Hubble's observing work prior to its launch. As HST changed over its time on orbit, so did these crucial facilities. This chapter also examines the European Space Agency's role in HST and the financial cost of the program.

As a unique and prominent astronomical facility with high demand for observing time and data, HST has driven change within astronomy as recounted in chapter nine. To obtain time on Hubble, astronomers have formed bigger research teams. The creation of STScI gave scientists a powerful voice in the running of HST, and the model has been adopted for similar facilities. NASA, for its part, has become the major force in funding astronomy in the United States. Both NASA and STScI have been involved in opening astronomy to female astronomers and also to scientists from visible minorities, but that effort has not always been easy. Where once observatories were private and data were the property of individual observers, HST as a public facility has opened data availability to the public.

While HST has long been known as an example of Big Science, this book will argue that it has also helped create what I call mass science by encouraging the creation of larger teams in astronomical studies and by making astronomical data available to the public. Hubble's high profile has raised the prominence of astronomy at a time when the numbers of professional astronomers have been growing. NASA has fostered this growth by providing financial support to astronomers using HST and other space telescopes and by creating the infrastructure that supports these instruments. Thanks in part to its prominent status in the early years of the internet, HST has allowed large numbers of people who had never looked through a telescope to explore the heavens in the comfort of their own homes. The fact that the internet came into wide use in the early years of Hubble operations made HST an early star of the online world and had a major impact on HST's relationship with astronomers and, more importantly, the public at large.

Hubble also was a key part of the Space Shuttle Program because of the six Shuttle missions that deployed and serviced it. Many of the techniques developed to help astronauts keep HST flying were applied to build the International Space Station (ISS). This book will discuss the evolution of HST servicing that started well before the first servicing mission. It will also explore the little-known processes involved in choosing the instruments that were placed on board HST during those servicing missions. While those changes to Hubble have been well publicized, the infrastructure that supported it on the ground is not as well known, and so a major theme of this study is the evolution of that infrastructure, especially the control center at Goddard and the science center for Hubble at STScI.

HST is one of the most famous projects undertaken by any space agency. Although it is a robotic spacecraft, it was regularly visited and serviced by astronauts. It was not the first telescope to fly in space, but it was the first designed to meet public expectations of images of various objects populating our universe. Its main mission was to observe the universe in ways previously not possible, and the data it has returned have sharpened and expanded humanity's view of the universe while raising new questions about its nature. Space telescopes that are following Hubble are taking different forms and have different purposes.

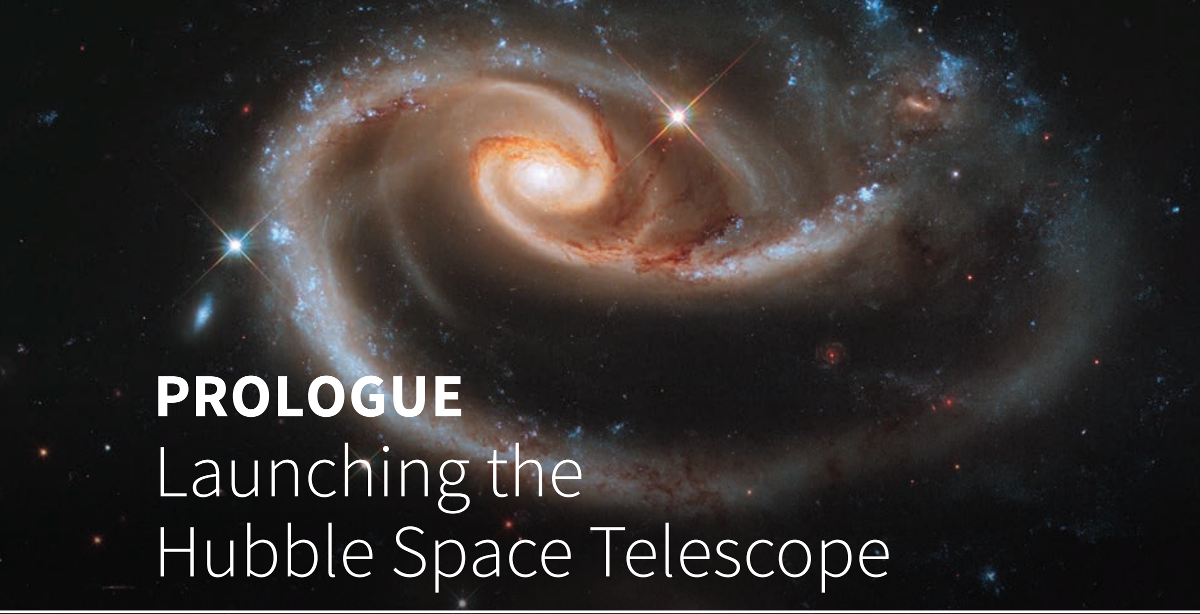
We have already learned that the creation of HST held many lessons about large scientific programs, and its lengthy period of operations in space contains many more lessons about high-profile science that are recounted in the pages that follow.

ENDNOTES

1 Spitzer quotation from "Astronomical Advantages of an Extra-Terrestrial Observatory," Project RAND, 30 July 1946. Bahcall was quoted in Timothy Ferris, "The Space Telescope: A Sign of Intelligent Life," *New York Times* (29 April 1990): A1.

2 Section 203 (a)(3), National Aeronautics and Space Act of 1958, Public Law No. 85-568, 72 Stat., p. 426. Signed by the President on 29 July 1958, Record Group 255, National Archives and Records Administration, Washington, DC; available in NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, DC (hereafter "HRC").

3 Robert W. Smith, *The Space Telescope: A Study of NASA, Science, Technology, and Politics* (Cambridge: Cambridge University Press, 1989). Cambridge published a paperback edition of this book with additional material in 1993. This work uses the 1993 edition for reference.



PROLOGUE
Launching the Hubble Space Telescope

▲ In December 2010, WFC3 recorded this view of the UGC 1810 galaxy within the constellation Andromeda. (NASA/ESA/Hubble Heritage Team [STScI/AURA]: heic1107a)

One of the most anticipated launches of the Space Shuttle era took place on Tuesday, 24 April 1990. After many delays, including one scrubbed launch attempt two weeks before, the Space Shuttle orbiter Discovery and its crew of five astronauts left Launch Complex 39B at John F. Kennedy Space Center in Florida at 51 seconds past 8:33 a.m. eastern daylight time atop a thundering pillar of brilliant flame, piercing a cloud as it rose through a generally clear sky.[1] Soon the Shuttle tilted nearly due east en route to an orbit at a standard inclination of 28.45 degrees from the equator. Nearly 9 minutes after launch, the Shuttle engines stopped firing and Discovery cast off its fuel tank as it coasted up to what was then a record altitude for a Shuttle of 618 kilometers (384 statute miles), an orbit that was circularized at that altitude with a thruster firing three quarters of an hour after launch.[2]

The focus of excitement around the launch was Discovery's payload, a huge satellite known as the Edwin P. Hubble Space Telescope (HST) that nearly filled the Shuttle's payload bay. While a number of space telescopes had flown starting in the 1960s, many people inside and outside the astronomical community looked forward to the deployment of the HST, which would be much more powerful and versatile than any previous astronomy satellite. The National Aeronautics and Space Administration (NASA) began working in earnest on the space telescope in 1977, and it became an international project when the European Space Agency (ESA) signed on that year as a partner on the space telescope.[3]

As launch day approached, the news media provided lavish coverage of the Hubble Space Telescope, explaining that it weighed nearly 11,000 kilograms

▲ The Space Shuttle Discovery carrying the Hubble Space Telescope into space on the STS-31 mission shortly after launch from Kennedy Space Center on 24 April 1990. (NASA: KSC-90PC-0633)

(24,000 pounds) and was 13.2 meters (43 feet) long and 4.2 meters (14 feet) in diameter, comparable in size to a school bus or a railroad tank car. Hubble's 2.4-meter (94-inch) main mirror was designed to direct light to a 0.3-meter (12-inch)-diameter secondary mirror that in turn reflected light to the telescope's five science instruments and its three Fine Guidance Sensors (FGS). The space telescope was reported to cost $2.1 billion and was expected to operate for 15 years or more. Many media reports highlighted the accuracy and smoothness of the main mirror—quoting the statement of its maker that if the mirror were enlarged to the size of Earth, it was so smooth that its highest peak would only be five inches (127 millimeters) tall.[4]

Some of the media accounts also tried to predict what the space telescope would discover as it looked at everything from nearby planets to objects at the fringes of the universe. The *Washington Times* said HST would tackle questions including: "How did the universe start? How will it end? Are there other worlds?"[5] *USA Today* also speculated on Hubble's ability to find planets orbiting other stars. Both the *New York Times* and *Washington Post* compared HST's effect on astronomy to Galileo's first glimpses of the heavens with the newly invented telescope back in 1609.[6]

Astronomers involved with the program also weighed in. "If we are disappointed, it's not the telescope's fault or our fault," astrophysicist John N. Bahcall of the Institute for Advanced Studies in Princeton, New Jersey, told the *New York Times* magazine. "It will be because of a lack of imagination on the part of God."[7] Lennard A. Fisk, NASA Associate Administrator for Space Science,