EVEN FURTHER

Hubble and the Nancy Grace Roman Space Telescope — What They're Capturing, and What Comes Next

The same glass, thirty-six years apart.



Douglas B.

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Douglas J. Brownfield

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This book was written with the assistance of AI tools, working from the author's own questions and editorial direction, and from a research record built for this book from primary sources — NASA, ESA/Hubble, and the Space Telescope Science Institute's own pages, timelines, and releases.

The telescope facts in this book are stated as of

move; the full statement of the snapshot, and of what was left open and why, is The Snapshot Statement in the back matter. The free site editions of this book are updated in place as the record changes, each with a version line and a date.

1. Both telescopes are still working, and their records

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The cover image is the Pillars of Creation as revisited by Hubble's Wide Field Camera 3 in 2014. Its credit line is carried in the Plate Credits (Plate 2).

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Introduction — Two Telescopes, One Mirror, One Woman

This book is about two telescopes that share more than a mission. The Hubble Space Telescope and the Nancy Grace Roman Space Telescope were built, thirty-six years apart, around primary mirrors of exactly the same diameter: 2.4 metres. The same glass, in size at least — and almost nothing else about them is the same.

Hubble is the elder. It launched in April 1990, was designed for a fifteen-year mission, and is still working in its thirty-seventh year. It observes in ultraviolet, visible, and near-infrared light. It has been repaired and rebuilt by astronauts five times. Today it flies on a single gyroscope, circles the Earth about every 95 minutes at below 500 kilometres and falling, and remains so heavily requested that about six or seven proposals compete for every available slot. Its archive, as of 2026, holds more than 1.7 million observations and over 477 terabytes of data, and the papers written from it number more than 23,000.

Roman is the newcomer. It launched on 30 August 2026 and is, as this book goes to press, travelling to its station a million miles from Earth and being checked out instrument by instrument. Where Hubble looks closely at one small patch of sky at a time, Roman takes in a field of view at least 100 times larger with each exposure, at comparable sharpness — and its mirror, the same 2.4 metres across, weighs about 80 per cent less than Hubble's. Hubble finds and examines. Roman will census: whole populations of galaxies, stars, and planets, counted by the tens of millions. Neither telescope does the other's job. Roman

has no ultraviolet capability at all, and ultraviolet is the light Hubble sees better than anything else flying.

Behind both of them stands one person. Nancy Grace Roman joined the young NASA, became its first chief of astronomy and the first woman to hold a leadership position there, and spent two decades building the institutional case for a great telescope in orbit — the campaign that produced Hubble. Her colleague Ed Weiler called her the Mother of Hubble. She died on Christmas Day 2018, aged 93. In May 2020, NASA named its next great observatory for her. She is the hinge of this book, and she gets a chapter of her own between its two halves.

A word about dates, because this book needs one. Everything in it is a snapshot as of November 2026. Hubble's totals move every month. Roman has not yet produced a single science image, and none will be presented here as one: its first are expected by early 2027, and what this book can show until then is launch photography, clean-room photography, and engineering test frames, each labelled for what it is. Hubble's ending is likewise undecided. Its orbit is decaying, its predicted re-entry window is 2033–34, and in October 2026 NASA formally asked industry whether a commercial mission could boost it, service it, or dispose of it safely — with responses due on 30 November 2026, inside this book's own production window. Where the record is open, the book leaves it open and says so.

What follows is in two parts. Part One is Hubble: the long argument that built it, the flaw that nearly ended it, the repairs that saved it, what it found, and the question now hanging over its last years. Part Two is Roman: the namesake, the gift of

hardware that reshaped it, the wide eye it carries, its launch, and the census to come.

It is also a visual book, and the plates carry half the telling. Hubble's signature images appear throughout Part One with their full official credit lines printed beneath them — that credit is not a courtesy but the condition on which NASA, the Space Telescope Science Institute, and the European Space Agency make the images free to use. The deep fields are set in sequence, so the reader can watch one telescope stare at the same near-nothing for thirty years and count what accumulates. Roman's pictures, for now, are of a different kind: a rocket leaving Florida, an observatory in a clean room, a ring of deliberately unfocused stars from its first photons. The contrast is the honest state of things in November 2026 — one telescope with a third of a century of captures behind it, one whose first true capture is still months away.

Thirty-six years apart, two telescopes carry the same-sized mirror into the dark — and between them, they are still changing what the word "further" means.

Part One — Seeing Further

Chapter 1 — The Long Argument

The idea of putting a telescope above the atmosphere is older than the rockets that could do it. In 1923, the German rocket pioneer Hermann Oberth mentioned propelling a telescope into Earth orbit in his book on rocket flight to the planets. The serious case, though, was made in 1946 by Lyman Spitzer Jr., a Princeton astrophysicist, who set out in a paper what an observatory above Earth's turbulent air could do: see steadily, in wavelengths the atmosphere blocks, without weather or daylight imposed by a rotating planet beneath it. Promoting that idea became, in NASA's phrase, a driving focus of his long career, and he is conventionally called the father of Hubble.

An idea, however, is not an institution. Spitzer supplied the argument; the person who turned it into committees, budgets, and congressional testimony was Nancy Grace Roman. Roman joined the fledgling NASA and, by 1960, was its first Chief of Astronomy — and its first female executive, the first woman in a leadership position at the agency. For the next two decades she led the science and planning committees for what was then called the Large Space Telescope, brought scientists and engineers into the same rooms, briefed executive branch officials, lobbied NASA's own leadership, and wrote the testimony when NASA representatives appeared before Congress. Her pitch, as she liked to put it, was that for the price of one night at the movies each year, each American would receive fifteen years of exciting discoveries. That line is a quip, not a transcript, but it captures the strategy: spread the cost across every citizen and the benefit across a generation. She also made technical calls that lasted. She pushed, for instance, to fit

charge-coupled devices — CCDs — as the telescope's image sensors in place of the older sensor technology then standard, a decision the finished observatory would vindicate.

The scientific community formalised its support in 1969, when a National Academy of Sciences report, *Scientific Uses of the Large Space Telescope*, endorsed the project; Spitzer had spent years gathering astronomer support and answering critics. In 1974 the first working-group meeting took up concepts, budget, and technical requirements, and the Science Working Group set the ambition plainly: interchangeable instruments, resolving a tenth of an arcsecond, working across ultraviolet, visible, and infrared light. It also settled the design decision that would eventually save the observatory's life. Hubble was planned from the start to be serviced — taken apart and upgraded in orbit by astronauts. Astronauts were training for servicing missions as early as 1979. No other major observatory has been built on that principle, and in 1993 it would make the difference between a failure and a recovery.

The resolution target deserves a plain-English translation, because a tenth of an arcsecond is not a unit anyone feels. An arcsecond is 1/3,600 of a degree. A tenth of one is the apparent size of a coin seen from several hundred kilometres away — fine enough to split close double stars, resolve the discs of the giant planets into weather, and read the crowded cores of distant galaxies star by star. The working group was not asking for a somewhat better telescope. It was asking for an instrument an order of magnitude steadier than the atmosphere allows anything on the ground to be, and it was asking in 1974, before the agency that would build it had flown anything like it.

Money shrank the telescope before it built it. Post-Apollo budget pressure in the 1970s forced the primary mirror down from 120 inches (3 metres) to 94 inches (2.4 metres); NASA's own history attributes the reduction to budget constraints. A persistent piece of folklore holds that the size was dictated by spy satellites. The defensible version is narrower: Hubble drew on the same industrial base and mirror-making technology developed for reconnaissance satellites — firms such as Perkin-Elmer and Kodak were the era's large-optics houses for both civil and surveillance work — but the telescope itself was an unclassified, purpose-built observatory, and its diameter was set by its budget, not by another programme's hardware.

Europe came aboard in 1975. The European Space Agency provided about 15 per cent of the funding, contributing the Faint Object Camera and the solar arrays, in return for a guaranteed minimum of 15 per cent of observing time for European astronomers — a partnership that has held for the observatory's entire life. In 1977, Congress approved funding to build the telescope, and the project formally got under way. Grinding of the 2.4-metre primary mirror began in December 1978 at Perkin-Elmer in Danbury, Connecticut. The mirror is Ultra-Low Expansion Glass, 828 kilograms of it, figured to hold a focal length of 57.6 metres folded into a tube 13.2 metres long — about the length of a large school bus. Its aluminium reflecting coat is some three millionths of an inch thick, overcoated with magnesium fluoride to lift its ultraviolet reflectivity.

The industrial-base point deserves one more sentence, because it produced a quiet insurance policy. Perkin-Elmer won the contract to build Hubble's flight mirror; Kodak, the losing bidder and the other great optics house of the reconnaissance era, built

a backup mirror instead. The backup was figured correctly. It never flew — by the time anyone knew the flight mirror was wrong, the telescope was in orbit and the cheaper path was to correct the light, not replace the glass — but its existence is a reminder that the flaw of 1990 was never a failure of the era's mirror-making as such. The craft could do the work. One measuring instrument, inside one contractor's process, said the work was other than it was.

In 1983 the Large Space Telescope was renamed for Edwin Hubble, the astronomer whose name attaches to the expansion of the universe, and the Space Telescope Science Institute began operations at Johns Hopkins in Baltimore, created to judge proposals and run the science. The institute mattered more than its administrative description suggests. A telescope above the atmosphere, oversubscribed from birth, needed a standing body to decide whose questions got asked — and to run the observatory as a public instrument rather than a project team's private one. That arrangement, an independent science institute operating a national facility, became the template later observatories inherited, and it is why Hubble's data have always flowed into a public archive rather than a filing cabinet. The industrial work was spread widely: Marshall Space Flight Center led design and development, Perkin-Elmer built the optical telescope assembly and the fine guidance sensors, Lockheed built the spacecraft structure and integrated the telescope, and Goddard led instrument design and ground control — dozens of contractors across 21 states and 12 countries. By 1985 the telescope was assembled and ready.

It then waited. On 28 January 1986 the shuttle *Challenger* was lost, the fleet was grounded for 32 months, and Hubble's launch

slipped with it. The stand-down was not wasted: solar cells were improved, the aft shroud was modified to make instrument swaps easier, computers and communications were upgraded, and the observatory was stress-tested further. The delay carried a cost measured in years, but the telescope that finally flew was better than the one that had been ready in 1985.

The argument had taken forty-four years, from a paper in 1946 to a telescope waiting on the ground — and the telescope it produced had been built, deliberately, to be visited.

Chapter 2 — Launch, and the Flaw

Hubble left Earth on 24 April 1990, aboard the space shuttle *Discovery* on mission STS-31, with five astronauts, from Kennedy Space Center. The next day it was deployed, lifted from the payload bay by the Canadian-built robotic arm, into a circular orbit roughly 570 kilometres up, inclined 28.5 degrees to the equator. It carried five instruments: the Wide Field and Planetary Camera, its main imager; the Faint Object Camera, Europe's contribution and the highest-resolution ultraviolet-visible camera of its era; two spectrographs, the Faint Object Spectrograph and the Goddard High Resolution Spectrograph, for spreading starlight into its component colours; and the High Speed Photometer, built to measure brightness flickering on millisecond timescales. It weighed 11,110 kilograms at launch. It had been designed for a fifteen-year mission.

The machine itself rewards a moment's attention, because its numbers are human-scale. It travels at about 27,000 kilometres an hour and completes an orbit in roughly 95 minutes, which means its day is an hour and a half long and half of every day is night. Its two solar arrays generate about 5,500 watts in sunlight; the observatory's average draw is about 2,100 watts — roughly a hair dryer's worth — and six nickel-hydrogen batteries carry it through the 25 minutes of eclipse in each orbit. Light falls on the 2.4-metre primary, reflects to a secondary mirror just 0.3 metres across and weighing 12.4 kilograms, and comes back through a hole in the primary's centre to the instruments waiting behind it.

Three fine guidance sensors lock onto guide stars to hold the whole assembly steady, and reaction wheels turn it — the telescope carries no thrusters for pointing, and slews by spinning internal wheels against its own mass. Its launch mass of 11,110 kilograms is often rendered as about two adult elephants; servicing would eventually add roughly 3,000 pounds of new equipment to that figure, growth that is itself a record of five visits' worth of new capability. Nothing about the design was exotic. It was a careful, conservative telescope — which is part of why what happened next was so hard to believe.

First light came on 20 May 1990, and even at first sight the camera's images were already about 50 per cent sharper than what ground-based telescopes could produce. (The record of the starting orbit is itself a small lesson in how this book handles numbers: ESA's fact sheet gives the deployment altitude as about 570 kilometres, while some American retrospectives give figures nearer 612 kilometres for the early operating orbit — deployment versus early operations. The difference matters less than the direction: whichever figure opens the account, every later one is smaller.) The trouble showed itself quietly. Star images had a sharp core, but wrapped in a diffuse halo that should not have been there, and both imaging cameras showed the same distortion. If two different instruments see the same defect, the defect is upstream of both: in the mirrors.

On 27 June 1990, two months after launch, NASA announced the diagnosis: spherical aberration. Light reflected from the edge of the primary mirror was coming to a focus at a different point from light reflected from the centre. Instead of one focus, the telescope had a smear of them. By the failure literature's accounting, only about 15 per cent of a star's light was landing

in the tight core the design promised, against roughly 70 per cent intended. On 2 July NASA formed the Optical Systems Board of Investigation, chaired by Lew Allen, the director of the Jet Propulsion Laboratory, to find out how a mirror that had passed every test could be wrong.

The mirror, it turned out, had been polished superbly — to the wrong shape. Its edge was too flat, by about 2 micrometres: roughly one-fiftieth the width of a human hair, spread across a surface 2.4 metres wide. That error sounds like nothing until it is set against the tolerance the mirror was built to, which it exceeded tenfold. A mirror is a machine for agreeing about where light goes, and an error of 2 micrometres is enough to break the agreement.

The cause was not the polishing. It was the measuring. During fabrication, the mirror's figure was defined by an instrument called a reflective null corrector — a device that simulates the perfect mirror's behaviour so the real one can be ground to match. Investigators found that corrector still undisturbed in its 1981 configuration, nine years on, and reverse-engineered the flaw from it: the corrector had been mis-assembled, with a lens spacing error of 1.3 millimetres. (Accounts derived from the investigation add a vivid detail — that a spacing measurement was thrown off where a laser reflected from a spot on a metering-rod end cap whose coating had flaked. The 1.3-millimetre error itself is NASA's stated finding; the flaked coating belongs to the investigation reporting.) The mirror had been ground, faithfully and precisely, into the shape a faulty measuring instrument described.

The harder finding was organisational. The reflective null corrector had not been the only test. Two auxiliary devices — a refractive null corrector and an inverse null corrector — had both, during fabrication, indicated spherical aberration in the mirror. Those results were discounted in favour of the primary instrument's readings, and, as the board found, the discrepant data never reached the managers who might have acted on it. The flaw in Hubble was, in other words, two flaws: a mis-assembled instrument, and a system in which contrary evidence could be set aside without anyone in authority knowing it existed. The glass was honest. The measurement chain was not.

Even flawed, the telescope worked. In August 1990, still trailing its halo, Hubble resolved the ring around Supernova 1987A, the exploded star that had been the brightest supernova visible from Earth in centuries. In October 1990 the first Hubble science paper was submitted — Tod Lauer's study of the environment of a suspected black hole in the galaxy NGC 7457. Astronomers learned to extract real science from the blurred images, and the archive of the broken years is not worthless. But the observatory that had been sold to the public as the sharpest eye ever flown was producing, in its most visible output, visibly soft pictures, and everyone who had funded the forty-four-year argument knew it.

There was also a scheduling fact pressing on everyone involved, though it is rarely mentioned in accounts of the flaw. Hubble had been designed for a fifteen-year mission, and the clock on that design life was already running. Every year spent blurred was a year subtracted from a finite total — and the instruments, gyroscopes, and batteries were ageing on the same schedule

whether the images were sharp or not. A fix that arrived in 1998 would have rescued a telescope with much of its planned life already spent. A fix that arrived in 1993 would hand back nearly the whole mission. The repair, when it came, would have to be early as well as right.

What saved Hubble was not a better mirror. The mirror could not be swapped; it was never designed to be. But the instruments behind it had been designed for exactly that, and the mirror's flawed light could be intercepted and corrected downstream, before it reached them. That distinction — an irreplaceable mirror feeding replaceable instruments — was the whole game.

Chapter 3 — The Repair

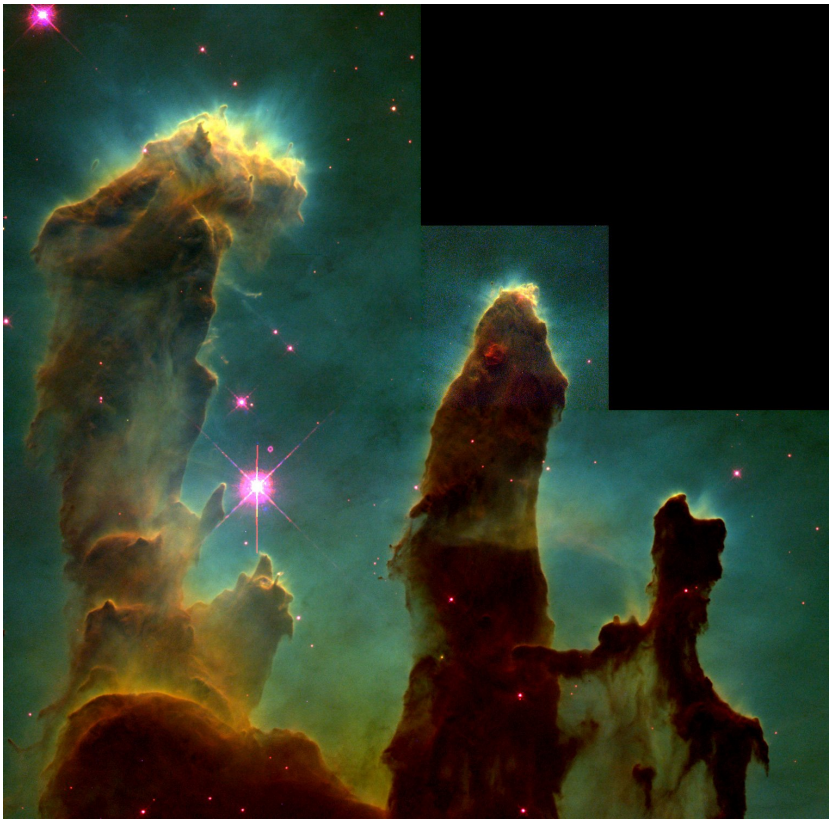


Plate 1 — Pillars of Creation (original). Three columns of cold gas in the Eagle Nebula, some 6,500 to 7,000 light-years away, lit by young massive stars, with newborn stars emerging from evaporating globules — "EGGS" — at the columns' tips. The Wide Field and Planetary Camera 2, the camera built to correct Hubble's flawed mirror, exposed this image on 1 April 1995; it was released on 2 November 1995.

Credit: Jeff Hester and Paul Scowen (Arizona State University), and NASA/ESA

The repair flew on 2 December 1993. Servicing Mission 1, mission STS-61 aboard *Endeavour*, carried seven astronauts

who would make five spacewalks totalling more than 35 hours — at the time, one of the most complex missions the shuttle programme had attempted. They were not swapping a part. They were fitting a prescription.

It is worth pausing on why a prescription was even possible. Hubble had been designed, from the 1970s working groups onward, to be serviced: its instruments were built as replaceable units meant to be swapped in orbit, and astronauts were training for servicing missions from 1979, a decade before launch. When the mirror proved flawed, that design decision converted a catastrophe into a work order. A monolithic telescope with the same flaw would simply have been a failed telescope, written off in place. Hubble could be opened. The repair mission was not an improvisation after disaster; it was the contingency the designers had built the whole observatory around, flown three and a half years after deployment.

What COSTAR restored, instrument by instrument, is worth naming, because the three instruments it served were not spares. The Faint Object Camera was Europe's contribution and the highest-resolution ultraviolet-visible camera of its era. The Faint Object Spectrograph spread the light of faint objects from the ultraviolet toward the near-infrared. The Goddard High Resolution Spectrograph was a ultraviolet specialist of the highest spectral resolution. Through 1993 all three had been looking through the aberration with no remedy of their own; each received, from COSTAR, its own pair of corrective mirrors, figured for its own light path. All three went back to work — and all three, in time, would be retired honourably by replacement rather than by failure: the two spectrographs in 1997, the Faint Object Camera in 2002, as the last original

instrument aboard.

The correction came in two forms, and the standard analogies are accurate enough to keep. The first was a replacement camera, the Wide Field and Planetary Camera 2, built with the aberration measured and compensated inside its own optics — a contact lens, ground for one specific eye. The second was COSTAR, the Corrective Optics Space Telescope Axial Replacement: a refrigerator-sized unit that took the place of the High Speed Photometer and deployed pairs of small mirrors — described in NASA's history as nickel- and quarter-sized — into the light paths of the three instruments it did not replace: the Faint Object Camera, the Faint Object Spectrograph, and the Goddard High Resolution Spectrograph. COSTAR was the spectacles; WFPC2 was the contact lens. The High Speed Photometer, it is worth recording, gave up its seat for the spectacles: the instrument sacrificed so that the others could see.

The crew also fitted new solar arrays — the second-generation arrays, SA2 — and attended to gyroscopes and other maintenance. The division of labour across the five spacewalks is worth a sentence, because it shows the mission's true shape: this was not one repair but a programme of work — a camera exchanged, a refrigerator-sized optical bench installed in a vacated instrument bay and its arms deployed into three separate light paths, power hardware renewed, pointing hardware serviced — each task useless without the others, and the whole of it choreographed to the minute. Missions since have been longer and further away; few have carried a payload of consequence this concentrated. Hubble was released back into its orbit, and then everyone waited for the pictures. On 13 January 1994, NASA announced the result: the aberration was

corrected, the images crisp and clear. It is difficult to overstate what that announcement closed. A project that had become a public byword for expensive failure was, in the space of one mission, again what it had been promised to be: the sharpest astronomical eye humanity had ever operated.

Technically, COSTAR deserves a clarifying note, because it is often misdescribed as a camera or a lens. It took no images and gathered no science of its own. It was corrective optics and nothing else: a set of small, precisely figured mirrors on deployable arms, positioned to intercept the flawed light before it reached three of the original instruments and re-shape each beam on its way in. Each instrument it served got its own pair of mirrors, figured for that instrument's light path. The mirrors could be small because they intercepted only the narrow pencil of light bound for one instrument — correcting the beam where it was narrow, not where it was wide. That economy, correcting the light late with small optics instead of refiguring the great mirror, is the engineering idea at the heart of the whole rescue. When later instruments arrived with the correction built into their own optics, COSTAR's arms had nothing left to correct — which is why, sixteen years after its installation, a later crew could unplug it and bring the era of the spectacles to a close.

The proof entered the culture the following year. Working through the repaired camera, astronomers imaged three columns of cold gas in the Eagle Nebula, some 6,500 to 7,000 light-years away — the Pillars of Creation — exposed on 1 April 1995 and released that November. The columns stand where massive young stars nearby are evaporating them; at their tips, dense globules of gas — evaporating gaseous globules, EGGS in the literature's unlovely acronym — are boiling away to expose

newborn stars inside. The image became the observatory's public face, reproduced beyond counting. But its first significance was narrower and more important: the Pillars were taken with WFPC2, the camera built to carry the correction, which is why they belong in this chapter. They are what a fixed telescope looks like. The same camera went on to take the Hubble Deep Field, and most of the observatory's 1990s icons, and it kept working until 2009. It now sits in the Smithsonian National Air and Space Museum, described there, fairly, as the camera that saved Hubble.



Plate 2 — Pillars of Creation (revisit). The same field, imaged again in visible light by the Wide Field Camera 3 in September 2014 and released on 5 January 2015 for Hubble's 25th anniversary — sharper, wider, and showing a jet from a newborn star lengthened by some 60 billion miles since 1995. Set beside the 1995 frame at the same scale, it is the servicing story told in a single comparison.

Credit: NASA, ESA/Hubble and the Hubble Heritage Team

The Pillars also give this book its before-and-after. In September 2014, Hubble's third-generation camera, WFC3, returned to the same field and imaged it again, sharper and wider, for the observatory's 25th anniversary — in visible light, and in a near-infrared companion view that looks through much of the columns' dust to the stars forming inside it. Put the 1995 and 2014 frames at the same scale and the whole servicing story is visible in one comparison — and the field itself has changed in the interval: a jet from a newborn star in the frame had lengthened by some 60 billion miles between the two exposures. The telescope was repaired; the sky did not hold still for it.

COSTAR's own story ended quietly. Every instrument installed after 1993 carried its correction within itself, so by 2009 the spectacles were redundant, and on the final servicing mission the crew removed COSTAR to make room for a new spectrograph. COSTAR, too, is in the Smithsonian now, alongside the camera. The two devices that fixed the most famous flaw in the history of astronomy are museum pieces you can stand in front of — which may be the most fitting summary of the episode. The flaw was real, the fix was real, and both are history.

What the repair actually purchased was not an apology; it was thirty more years of work.

Chapter 4 — Five Visits

Servicing Mission 1 had been a rescue. The four missions that followed turned rescue into routine — except that nothing about them was routine. Each visit replaced instruments wholesale, and the practical consequence is worth stating plainly: by the end of the fifth visit, the telescope returning the best images in astronomy contained almost none of its original 1990 science hardware. Hubble was not maintained. It was successively rebuilt.

Servicing Mission 2 flew on *Discovery* in February 1997 and widened the telescope's reach in wavelength. The Space Telescope Imaging Spectrograph, STIS, replaced the Faint Object Spectrograph, and the Near Infrared Camera and Multi-Object Spectrometer, NICMOS, replaced the Goddard High Resolution Spectrograph. Hubble gained proper near-infrared capability and a far more capable spectrograph: STIS, able to take spectra of many objects at once across ultraviolet, visible, and near-infrared light, became the observatory's principal black-hole hunter, reading the motion of gas around galactic nuclei. The crew also renewed engineering hardware — a recorder, a fine guidance sensor, a reaction wheel among it — because a servicing visit has always been two missions in one: new science instruments above, new plumbing below. NICMOS itself had a chequered career that previews the pattern of this chapter: its solid-nitrogen coolant ran out early, in 1999, after a thermal short in its dewar, and Hubble's infrared eye went blind until a later crew revived it with a mechanical cryocooler — a refrigerator, installed in orbit, to do the job the expended coolant no longer could. (An odd footnote of the era:

in October 1998, *Discovery* flew the Hubble Orbiting Systems Test — not a servicing mission, but a flight, with John Glenn aboard, to validate hardware planned for the next visit. Most timelines omit it entirely.)

The next visit had to be split in two, because the telescope failed while waiting for it. On 13 November 1999 the fourth of Hubble's gyroscopes failed, and the observatory put itself into safe mode and stopped doing science. A telescope that cannot hold its pointing cannot observe, and with too few gyros Hubble could not hold its pointing. Servicing Mission 3 became SM3A, an urgent December 1999 flight on *Discovery* whose crew replaced all six gyroscopes, fitted a new main computer — described in mission accounts as roughly twenty times faster than the one it replaced — six battery voltage and temperature improvement kits, a solid-state recorder, a new transmitter, a replacement fine guidance sensor, and fresh insulation. The split had a cost beyond the emergency: everything else planned for that visit, the new camera above all, waited more than two further years for the second half of the mission to fly.



Plate 16 — Eagle Nebula tower. A cold-gas tower nine and a half light-years tall in the Eagle Nebula, imaged by the Advanced Camera for Surveys for Hubble's 15th anniversary and released on 25 April 2005. It is a different structure from the Pillars, taken by the camera whose installation, in 2002, removed the last of Hubble's original instruments.

Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

SM3B followed in March 2002, aboard *Columbia*. Its centrepiece was the Advanced Camera for Surveys, ACS, which replaced the Faint Object Camera — the last of Hubble's original 1990 instruments to leave the observatory. ACS had roughly ten times the discovery power of the camera it succeeded, and it would go on to take the Ultra Deep Field. The crew fitted the new rigid, more powerful solar arrays the telescope still flies with, revived NICMOS with a mechanical cryocooler after its original coolant had run out early, and replaced the Power Control Unit — a job that required, for the first time, shutting the entire telescope down on orbit and bringing it back up. This flight also gave Hubble its last orbital reboost. No visiting vehicle has raised its orbit since 2002, a fact that decides the terms of Chapter 7.

On 1 February 2003, *Columbia* was lost on re-entry with its crew. Among the consequences: the final servicing mission, SM4, was cancelled in January 2004, because a flight to Hubble could not reach the International Space Station as a safe haven if the shuttle were damaged. Without SM4, the telescope's remaining instruments began to fail on schedule and then ahead of it. STIS lost power in August 2004. In January 2007 an electronics failure disabled the two most-used channels of ACS — though its far-ultraviolet Solar Blind Channel kept working, a partial survival that would matter in 2026, when that same camera made the decisive observation of Hubble's late career. Public and scientific pressure built, and on 31 October 2006 NASA reinstated the mission. Even then the failures kept pace: in September 2008, with SM4 weeks from launch, the unit that formats and routes Hubble's science data failed, the telescope went into safe mode again, and the mission stood down while

engineers prepared a flight-ready spare from a ground unit.

SM4 flew at last on 11 May 2009, aboard *Atlantis*, and it was the most ambitious of the five. The crew installed two new instruments: the Wide Field Camera 3, WFC3, the versatile imager that has since taken most of modern Hubble's pictures, including the 2014 Pillars; and the Cosmic Origins Spectrograph, COS, the most sensitive ultraviolet spectrograph ever flown, which took the slot vacated by COSTAR. WFC3's numbers state what a generation means in practice: working two channels, one for ultraviolet and visible light and one for the near-infrared, it is some 35 times more sensitive in the ultraviolet than the camera that saved Hubble, and between seven and sixteen times more efficient at making discoveries. It replaced that camera — WFPC2 came home in WFC3's place in the manifest — which closes a loop this book has been following since Chapter 3: the contact lens was retired by its own successor. Then they did something servicing had never attempted: they opened two dead instruments and repaired them at the level of their circuit boards, on orbit, with tools built for the purpose. STIS and ACS — both silent, neither designed to be serviced this way — were revived. The crew also replaced all six gyroscopes again, fitted new batteries, a fine guidance sensor, and a replacement for the failed data-formatting unit, renewed the insulation, and attached a soft-capture ring: a docking target for a future vehicle that might one day come to dispose of the telescope safely. Hubble was released on 19 May 2009, and its early-release images that September — the Butterfly Nebula, Stephan's Quintet, Omega Centauri — served as the receipt.

Read across all five manifests, a pattern emerges that explains the observatory's longevity better than any single mission does. No visit was purely a science upgrade and none was purely a repair. New instruments always arrived alongside new gyroscopes, batteries, recorders, insulation, or computers — the life-support renewed in the same flights that renewed the science. Hubble's operators never had to choose between keeping the telescope alive and keeping it current, because the servicing programme, from its 1970s conception, treated the two as one job. When the visits stopped, both kinds of renewal stopped together, which is why the chapters after this one are about rationing.

The instrument generations, compressed, tell the story: 1990's camera, spectrographs, and photometer; 1993 and 1997's corrected camera, imaging spectrograph, and infrared instrument; 2002 and 2009's survey camera, wide-field camera, and ultraviolet spectrograph. Five visits across sixteen years had turned a flawed telescope into a succession of new ones wearing the same mirror. The telescope even gained weight in the process — from 11,110 kilograms at launch to roughly 12,247 kilograms after SM4, three thousand pounds of accumulated new capability riding on the same 2.4-metre mirror.

And after May 2009, no one would ever come again — the shuttles retired in 2011, and everything Hubble has done since, it has done alone.

Chapter 5 — What Hubble Found



Plate 6 — Hubble Legacy Field. The widest of Hubble's deep views: some 265,000 galaxies reaching back to 500 million years after the Big Bang, woven from about 7,500 exposures across sixteen years and 31 observing programmes, spanning ultraviolet to near-infrared light. Released on 2 May 2019, from Advanced Camera for Surveys and Wide Field Camera 3 data. The eXtreme Deep Field lies inside this frame.

Credit: NASA, ESA, and G. Illingworth (University of California, Santa Cruz; UCO/Lick Observatory)

Start with the number the telescope was, in a sense, built to produce. Before Hubble, the measured expansion rate of the

universe was so uncertain that the universe itself could be anywhere from 10 to 20 billion years old — a range wide enough to swallow the ages of its own oldest stars. Hubble's Key Project set out to close that range by measuring Cepheid variable stars in other galaxies with a precision ground telescopes could not match, building the distance ladder rung by rung. The error bars shrank year by year, and the age of the universe settled at 13.8 billion years. Astronomy went from not knowing the age of everything within a factor of two to knowing it within a few per cent, and Hubble's measurements did most of that work.

The expansion story then took the turn nobody's instruments were built to expect. In 1998, two teams studying distant supernovae — Adam Riess's High-z Supernova Search Team and Saul Perlmutter's Supernova Cosmology Project — found, working mainly with ground-based telescopes, that the expansion of the universe is accelerating. Retellings often hand this discovery to Hubble outright; the record does not. Hubble supported the work, and then did something the discovery itself could not: it read dark energy's history. By measuring supernovae far enough away to see the universe as it was 9 billion years ago, Hubble showed that dark energy was already at work then — it is not a recent arrival — and that the expansion first decelerated under gravity and only began accelerating some five to six billion years ago, when dark energy overtook it. That pattern matches the behaviour of Einstein's cosmological constant. Riess, of the Space Telescope Science Institute and Johns Hopkins, shared the 2011 Nobel Prize for the acceleration discovery.

The measurement Hubble made famous is, at press time, also the site of a live dispute — and a November 2026 book should say

so. The local distance ladder, built on Hubble's Cepheid measurements and supernovae, puts the present expansion rate at about 73 kilometres per second per megaparsec; a 2026 consensus report from the Local Distance Network puts it at 73.50 ± 0.81. Rival distance ladders, using different stellar indicators and including Webb data, land nearer 70. The early universe, read through the European Space Agency's Planck satellite and the standard cosmological model, predicts 67.4. The gap between about 73 and 67.4 is around 9 per cent and now exceeds five standard deviations: too large, the argument runs, to be measurement error. In 2023–24 the Webb telescope checked Hubble's Cepheid photometry directly and agreed with it, ruling out the favourite mundane explanation — unrecognised crowding of stars in the Cepheid fields — at high significance. So the discrepancy looks less like a Hubble error and more like physics the standard model does not contain. The Hubble tension is unresolved, and it is, in part, Hubble's own measurement refusing to go away.

Black holes underwent a similar change of status: from suspected objects to a census. In 1992 Hubble imaged the accretion disk fuelling a suspected black hole in the galaxy NGC 4261. On 25 May 1994 it confirmed a supermassive black hole at the heart of M87 — a rapidly rotating, collapsed object pinwheeling gas at its core. In 1997 STIS caught the spectroscopic signature of the same phenomenon in M84. Across many galaxies the pattern consolidated into a rule: essentially every large galaxy carries a central black hole, and its mass tracks the mass of the galaxy's bulge. In August 2006, Hubble, the Chandra X-ray observatory, and ground telescopes together produced direct empirical evidence for dark matter in

the Bullet Cluster, where gravitational lensing showed the cluster's mass residing apart from its hot gas — mass where no visible matter was.

Hubble also, more or less single-handedly, opened the study of exoplanet atmospheres. In 2003 it watched the hot Jupiter HD 209458b evaporating, its atmosphere streaming away in a comet-like tail of hydrogen — the first evaporation of a planet's air ever observed. In 2007 it found the fingerprint of haze in the atmosphere of HD 189733b. In March 2008, NICMOS detected methane there: the first organic molecule identified on a planet of another star, followed within the year by carbon dioxide on the same world. In November 2008 came Fomalhaut b, among the first exoplanets ever imaged directly in visible light. A field that did not exist when Hubble launched now runs substantially on methods Hubble pioneered.

Closer to home, the same decades collected a set of firsts that rarely make the summaries. In July 1994 Hubble watched the fragments of Comet Shoemaker–Levy 9 strike Jupiter — the first collision of two Solar System bodies ever witnessed as it happened. In 1994 it found the first surface features on Saturn's moon Titan, and in 1996 on Pluto. In 1995 it detected oxygen in the atmosphere of Jupiter's moon Europa. In January 1996 it produced the first direct image of another star's surface — Betelgeuse, with an unexplained hot spot on it. Beginning in 2005 it discovered four of Pluto's five known moons, and new rings and moons of Uranus. And in 2002–03 it photographed one of its strangest sights almost by accident: the star V838 Monocerotis, which had briefly flared to some 600,000 times the Sun's brightness, lighting up shells of surrounding dust in expanding rings — a light echo, whose time-lapse turned the

dust around a star into a three-dimensional map. None of these results required the telescope to be the largest of its era. They required it to be above the atmosphere, sharp, and — above all — still there.

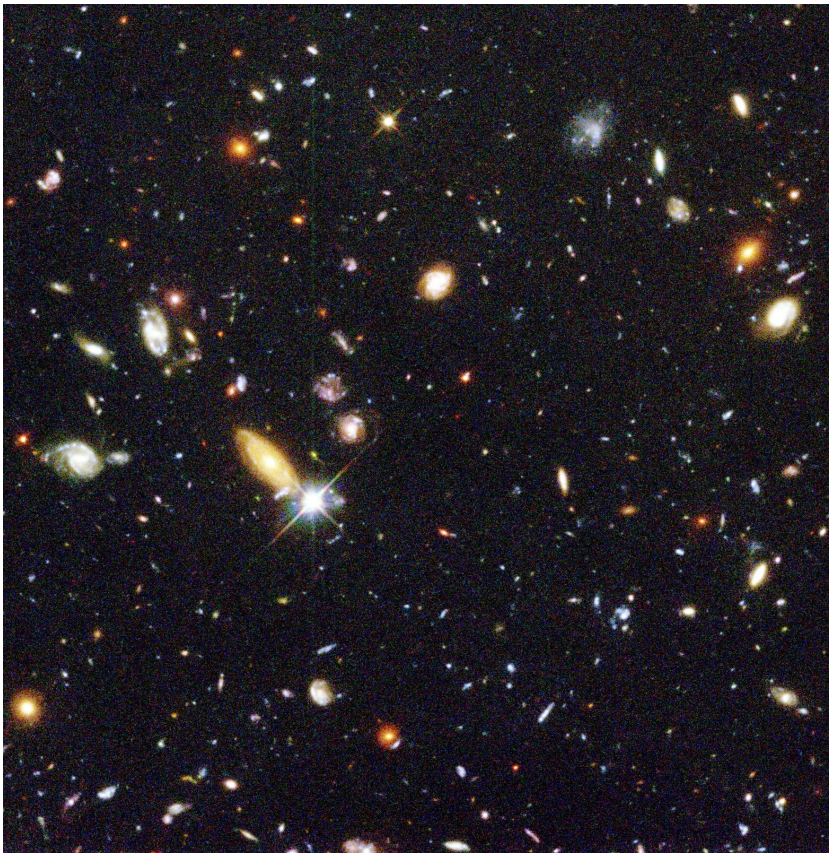


Plate 3 — Hubble Deep Field. Some 3,000 galaxies in a patch of apparently empty sky in Ursa Major — a field the size of a grain of sand held at arm's length — some of them among the youngest galaxies known. The Wide Field and Planetary Camera 2 took 342 exposures over ten days, 18 to 28 December 1995; the image was released on 15 January 1996.

Credit: Robert Williams and the Hubble Deep Field Team and NASA

And then there are the deep fields — the discovery engine, and a story about institutional nerve. In December 1995 the institute's director, Robert Williams, committed a large share of his Director's Discretionary Time to pointing the repaired telescope at a patch of sky chosen for its emptiness, for ten days. Colleagues feared a career-ending blank frame. The Hubble Deep Field, released in January 1996, held some 3,000 galaxies in a speck of sky the size of a grain of sand held at arm's length.

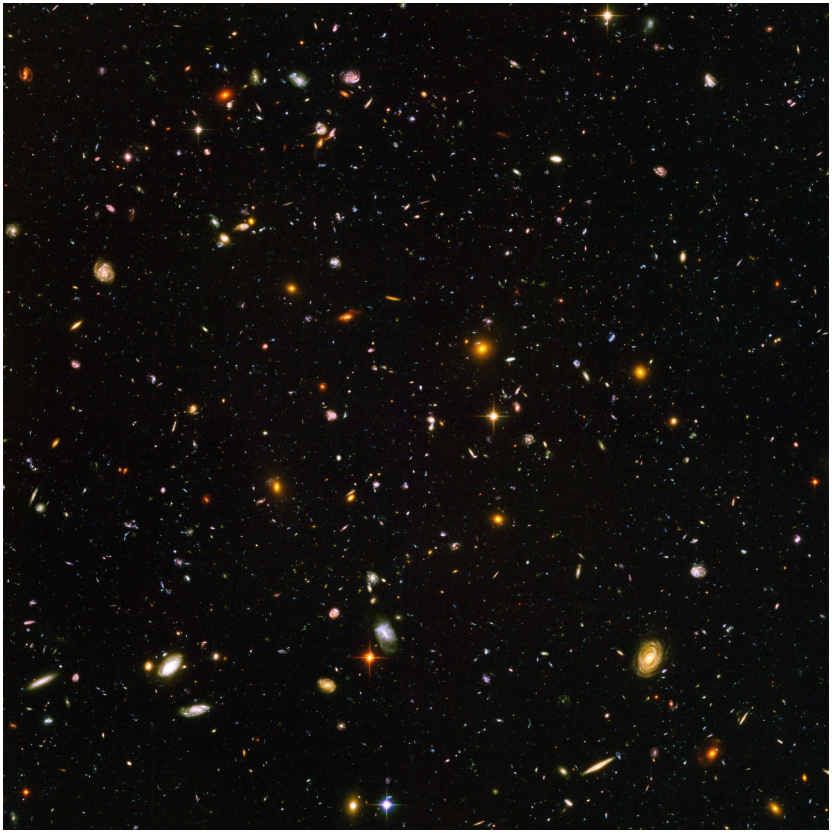


Plate 4 — Hubble Ultra Deep Field. About 10,000 galaxies in the constellation Fornax, in a million-second exposure built from 800 exposures across 400 orbits between 24 September 2003 and 16 January 2004, released on 9 March 2004. More than 500 of its galaxies date from less than a billion

years after the Big Bang. The Advanced Camera for Surveys took the visible-light image; NICMOS supplied an infrared companion view.

Credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

The gamble was repeated and deepened. The Ultra Deep Field of 2004 used 400 orbits and a million-second exposure to find about 10,000 galaxies, more than 500 of them from within the universe's first billion years.

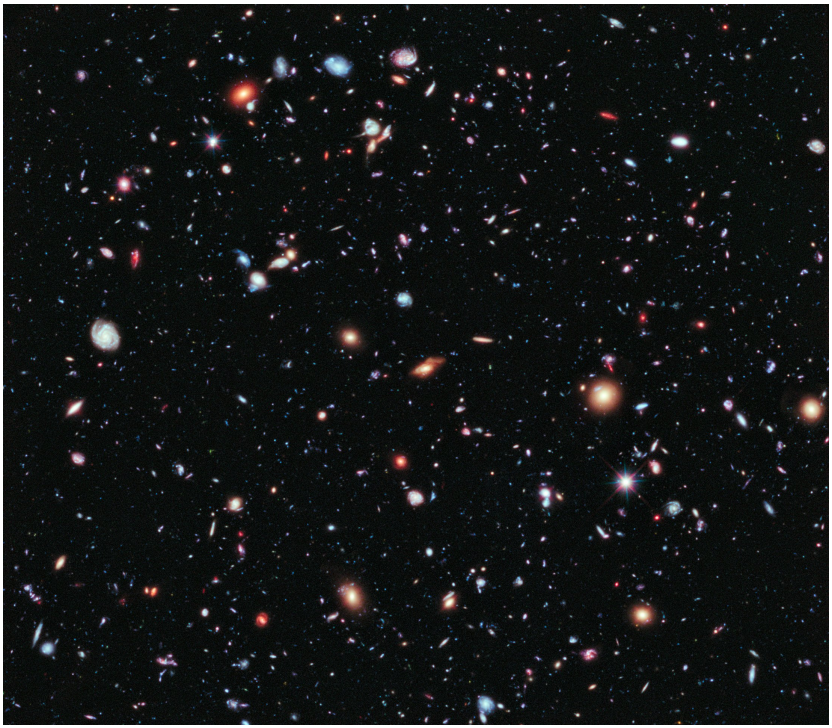


Plate 5 — Hubble eXtreme Deep Field. The deepest view Hubble has made: some 5,500 galaxies in the centre of the Ultra Deep Field, combining ten years of data and two million seconds of exposure between 2002 and 2012, released on 25 September 2012. Its faintest objects shine at one ten-billionth of the brightness the naked eye can detect. Advanced Camera for Surveys and Wide Field Camera 3 data.

Credit: NASA, ESA, G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University), and the HUDF09 Team

The eXtreme Deep Field of 2012 folded a decade of data — two million seconds — into the centre of that field, reaching some 5,500 galaxies and objects one ten-billionth as bright as the faintest the naked eye can see.

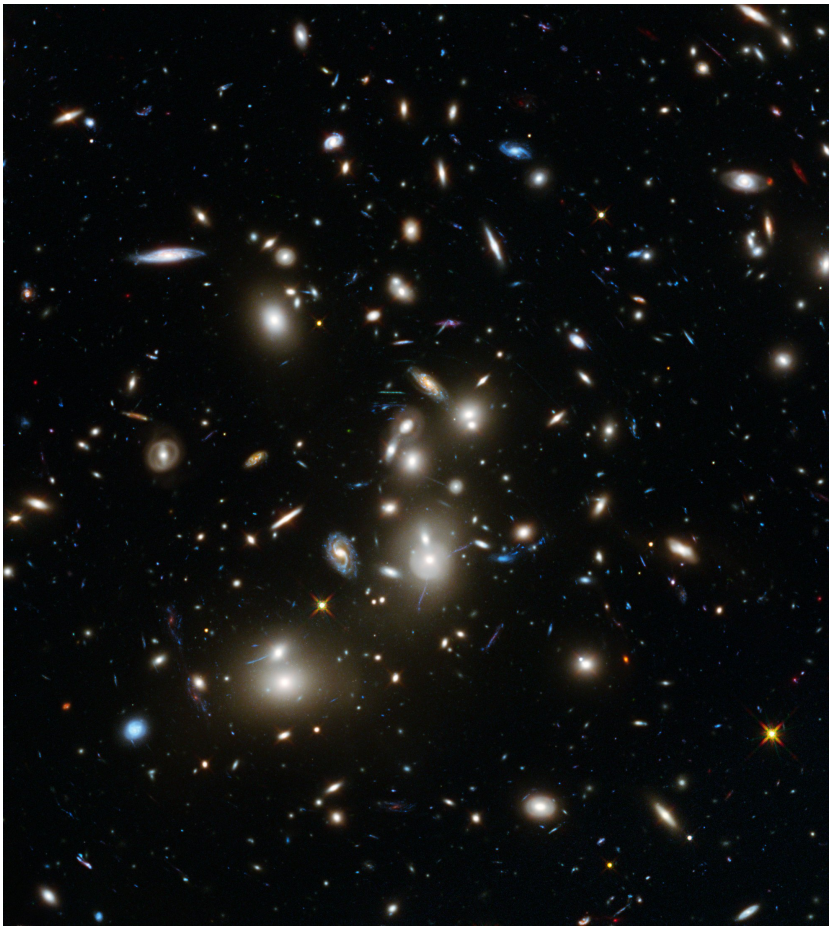


Plate 15 — Frontier Fields: Abell 2744, "Pandora's Cluster." ***A pile-up of galaxy clusters whose combined gravity acts as a lens, magnifying about 3,000 background galaxies, some more than 12 billion light-years away.***

The first image of the Frontier Fields programme — six clusters, three years, 840 orbits, working with the Spitzer and Chandra observatories — released on 7 January 2014, from Advanced Camera for Surveys and Wide Field Camera 3 data. Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI) *Rights-flagged plate (not captioned; for the build). Plate 8, the Carina Nebula panorama, blends Hubble's ACS data with ground-based colour data from CTIO carrying third-party rights (NOAO/AURA/NSF). It is flagged in the research report for exact-rights verification before any use, and will be cleared or swapped at build; the clean Plate 9 (Mystic Mountain, WFC3) covers Carina in the meantime.*

Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

The deep fields' logic extends through the Frontier Fields programme, which turned massive galaxy clusters into lenses: their gravity magnifies the still more distant galaxies behind them. Its first image, of the pile-up cluster Abell 2744 in 2014, showed about 3,000 background galaxies, some more than 12 billion light-years away. Lensing also delivered Earendel in 2022 — the most distant individual star ever seen, its light magnified thousands-fold by a foreground cluster, found not at the telescope but in archival data, in the RELICS survey's holdings. Hubble's archive, kept public at the Mikulski Archive for Space Telescopes, is itself an instrument: the millionth observation, in 2011, was spectroscopy hunting water in the atmosphere of the exoplanet HAT-P-7b, and discoveries continue to be mined from data years after it was taken.

Set the four deep images in sequence and they make the argument of this whole part in one spread: the same telescope, staring at nearly the same nothing, counting 3,000 galaxies, then 10,000, then going deeper, then — in the Legacy Field of 2019 — widening the frame to some 265,000 galaxies assembled

from 7,500 exposures across sixteen years. The Legacy Field literally contains the eXtreme Deep Field inside it. As of 2026 the archive behind all this holds more than 477 terabytes, and astronomers still apply for Hubble's time at about six or seven proposals for every slot available. The findings in this chapter are usually described as Hubble's discoveries; the deeper description is that they are the compound interest on a repair.

Chapter 6 — The Elder



Plate 11 — Veil Nebula. Filamentary shrapnel of a star that exploded about 8,000 years ago: a six-frame mosaic, about two light-years across, of one sliver of the 110-light-year Cygnus Loop. The Wide Field Camera 3 took the frames on 14 to 17 April 2015; the image was released on 24 September 2015, and a reprocessed version followed in 2021.

Credit: NASA, ESA, Hubble Heritage Team

Since 2009, Hubble's story has been a long exercise in a particular engineering craft: trading capability for lifetime, on purpose, one subsystem at a time. The craft began earlier than the last servicing mission. In August 2005, with three gyroscopes working, Hubble deliberately shut one down and began two-gyro science operations — banking the idle gyro's remaining life against the day the others failed. It was the first formal admission that the telescope's senses would be rationed, and it worked: two-gyro mode ran until the final servicing

mission refreshed the stock in 2009.

The failures since have been met the same way, from the ground, by people who cannot touch the machine. In October 2018 a gyro failure put Hubble in safe mode; the operations team diagnosed the misbehaving unit and had restored full science by 26 October 2018, working around the failed gyroscope rather than through it — an early rehearsal, though no one framed it that way at the time, for the one-gyro decision of 2024. In June 2021 the payload computer — the NSSC-1, hardware of 1980s design that coordinates the instruments — halted outright. For a month the telescope did nothing — safe mode, in the engineers' vocabulary: powered, stable, pointed safely, and scientifically silent — while engineers on the ground rehearsed the switch to backup hardware on a testbed, then executed it; full operations were restored by 17 July. That autumn the instruments lost their synchronisation messages and the observatory safed again; the team brought the cameras back one by one — ACS on 8 November, then COS and WFC3 — with all four active instruments restored by 6 December 2021, the fix delivered largely as instrument software changes rolled out from mid-December.

The largest rationing decision came on 4 June 2024. Of the six gyroscopes installed in 2009, three remained operational — but one of the three had spent six months returning faulty readings, claiming the telescope was slewing at maximum rate regardless of its actual motion, and repeatedly forcing safe modes, most recently on 24 May 2024. NASA's answer was to change how Hubble points: from then on it would operate on a single gyroscope, holding the second healthy gyro in reserve and monitoring the faulty third. Hubble was designed to do science

on one gyro — the mode had been test-demonstrated back in 2008 with no loss of image quality — and science resumed in mid-June. The costs are real but bounded: longer slews and lock-on times, less of the sky accessible at any given moment, and no tracking of moving targets closer than Mars. Science-press estimates put the price at roughly 12 per cent less observing time and up to a quarter less scientific output; the gain is measured in years of the remaining gyroscopes' lives. NASA put the probability of at least one working gyro through 2035 at better than 70 per cent. The reserve arrangement matters to how that figure should be read: if the flying gyroscope fails, the answer is a switch to the healthy spare, not the end of the mission — the rationing is designed so that its own most likely failure is already provided for.

On 19 September 2026, Hubble completed its 200,000th orbit — more than 5 billion miles travelled — and NASA marked the occasion with the telescope at work, hunting a gravitationally lensed supernova in the cluster MACS J0417. A year and a half earlier it had passed its 35th anniversary in orbit with a set of new releases: Mars, planetary nebulae, the Rosette, the barred spiral NGC 5335. The standing totals at that anniversary describe the scale of the working life behind the rationing: nearly 1.7 million observations of some 55,000 targets, more than 22,000 papers in print, and an archive already past 400 terabytes and growing toward the 477 terabytes recorded as of 2026. The elder is not commemorating itself. It is observing.



Plate 13 — Antennae Galaxies. Two colliding spiral galaxies, NGC 4038 and NGC 4039 — the nearest and youngest galaxy merger known — ablaze with newborn blue star clusters set in pink hydrogen gas. This best-ever version, combining Wide Field Camera 3 and Advanced Camera for Surveys data, was released on 11 November 2013; earlier versions date to 1997 and 2006.

Credit: ESA/Hubble & NASA

What keeps it indispensable is a band of light. Hubble works from about 0.1 to 2.5 micrometres — ultraviolet, visible, near-infrared. The Webb telescope, for all its power, sees no ultraviolet at all: its range begins at 0.6 micrometres, in the infrared. Roman, as Part Two will show, has no ultraviolet either. And no ground telescope can substitute, because Earth's

atmosphere blocks most ultraviolet light before it arrives. The hottest and most energetic phenomena in the sky announce themselves in UV: massive young stars, gas spiralling toward black holes, supernova shock fronts, the warm gas between and around galaxies that the Cosmic Origins Spectrograph reads in the light of background quasars, aurorae and weather on the giant planets, and the upper atmospheres of exoplanets, where escaping hydrogen is visible precisely in ultraviolet. COS itself is the sharpest expression of the niche: an ultraviolet-only spectrograph, at least ten times as sensitive as Hubble's previous ultraviolet instruments and up to seventy times so for the faintest objects. Hubble's ultraviolet sharpness and sensitivity remain, in the words of one astronomer quoted by *Science News*, the best thing the species has ever done at those wavelengths. No successor with comparable ultraviolet capability is expected before the proposed Habitable Worlds Observatory, a 2040s mission. When Hubble stops, it will leave a gap of a decade or more in a whole colour of light.

The working kit that carries this programme, as of late 2026, is four instruments and a guidance system that doubles as a fifth: WFC3, the main imager, working from ultraviolet through near-infrared; ACS, the survey camera, repaired in 2009; COS in the ultraviolet; STIS, the general-purpose spectrograph, likewise revived; and the three fine guidance sensors, which hold the telescope's pointing and, between pointings, do precision astrometry of their own — measuring stellar distances and the orbits of binary stars with an accuracy no other flying instrument matches, a second scientific career hidden inside a pointing device. Mission operations run from Goddard; science operations from the institute in Baltimore. There will be no

further astronaut visits — the shuttle fleet retired in 2011, and no servicing mission is scheduled or, with current vehicles, possible. Everything in the preceding paragraphs was achieved under that condition: a telescope beyond reach, kept at the frontier by software, procedure, and patience.

The emblem of late-life Hubble arrived on 5 January 2026, and it is a discovery made of an absence. Radio telescopes — FAST in China and the Very Large Array — had found a cloud of hydrogen near the galaxy M94, about 14 million light-years away: gas-rich, dark-matter-dominated, and, on the radio evidence, containing no stars at all. The object, named Cloud-9, would be the first confirmed example of a predicted class, a Reionization-Limited H I Cloud — a relic of early galaxy formation that never lit up. Confirming it required proving a negative, and that was Hubble's job: its Advanced Camera for Surveys searched the cloud and found the absence of stars the theory required. Cloud-9 stands as the first confirmed RELHIC: a galaxy that failed to happen, identified in Hubble's thirty-sixth year by the steadiness of its gaze. It is hard to think of another observatory whose headline result of the year was a measurement of nothing, made precisely enough to settle a question theory had left open.

That is the elder statesman's actual situation in late 2026: rationed, repaired by radio, still first in line for the hardest light there is — and still discovering things no one else can see.

Chapter 7 — The Open Ending

Hubble cannot save itself. It has no propulsion: no engine, no thrusters with which to raise or even maintain its orbit. Every metre of altitude it has ever gained after deployment was given to it by a visiting shuttle, and the last of those gifts came in 2002. Since then, the faint drag of the upper atmosphere has been pulling it down, orbit by orbit, year by year. Deployed at roughly 570 kilometres, it is now below 500 km and falling (late 2026), circling the Earth about every 95 minutes. NASA's current analysis, published in October 2026, predicts that Hubble is likely to re-enter the atmosphere in the 2033 to 2034 timeframe. A lifetime analysis from July 2026, quoted from the text of NASA's request for information, sharpens the shape of that forecast: a 10 per cent probability of re-entry by September 2032, and 50 per cent by December 2033. The Space Telescope Science Institute's own median forecast is the same: mid-2033.

The strange part is what will end the mission. It will not be the instruments. Hubble's hardware has repeatedly outlasted the estimates made for it, and the institute's 2025 assessment put the probability that at least two fine guidance sensors, one gyroscope, and three reaction wheels would still be working in 2030 above 90 per cent — with less than a 10 per cent chance of re-entry before 2030 on the same forecasting. Older forecasts of operations "into the 2030s" or "until 2030–2040" were statements about hardware, and on the hardware they may well prove right. In 2026 the binding constraint flipped: the telescope will probably outlive its orbit. The mirror is fine. The sky is fine. The altitude is not.

An uncontrolled end is not a tidy one. Hubble was never designed for controlled disposal, and a 2022 re-entry casualty study, cited in 2026 reporting, estimated that around 20 per cent of its mass — some 2.6 tonnes — could survive re-entry to the surface, with a casualty probability of roughly 1 in 330, against NASA's standard of 1 in 10,000 for uncontrolled re-entries. Those are reported study figures rather than NASA-confirmed numbers, but they explain why any serious conversation about Hubble's future now includes the end as one of its subjects. This risk arithmetic, as much as the science case, is why a controlled re-entry or disposal option stands as one of the three tracks in NASA's 2026 request. (One outlier analysis, by the astronomer Jonathan McDowell, allows re-entry as early as 2028 under high-drag assumptions — well outside the NASA and institute distribution, and noted here only so the reader knows the range of published argument.)

The rescue question has its own four-year history, and it runs in a circle. In 2022 NASA and SpaceX signed an unfunded Space Act Agreement to study boosting Hubble with a Crew Dragon — an idea that came from Jared Isaacman's Polaris Program and was offered at no cost to the government. NASA also sought other commercial concepts, and in 2023 a robotic servicing concept from Astroscale and Momentus was publicly offered. Then, on 4 June 2024 — the same day it announced one-gyro operations — NASA declined to pursue a reboost: having explored current commercial capabilities, in Astrophysics director Mark Clampin's words, "we are not going to pursue a reboost." Reporting of the decision cited substance behind the caution, including the risk that a visiting vehicle's outgassing could contaminate Hubble's ultraviolet-sensitive optics, and the

fact that the capture procedure had never been demonstrated.

The circle turned again. Isaacman, the reboost's original proposer, was confirmed as NASA Administrator in December 2025. By June 2026, agency officials — Shawn Domagal-Goldman, speaking to an advisory committee — were saying publicly that reboost costs looked lower than expected and that NASA was, after all, "open to a reboost." Read in sequence, the positions describe an agency arguing with itself in public across four years: a study welcomed in 2022, a door closed in 2024, the same door reopened in 2026 by a leadership that now included the man who had first proposed walking through it. Fresh in everyone's mind, though, is a cautionary precedent from the same season: NASA's commercial boost attempt for the Swift observatory, using Katalyst's LINK vehicle, concluded in September 2026 without raising Swift's orbit. Swift ended its science on 20 October 2026 and was expected to re-enter in early November. Whoever bids to save Hubble now does so in that attempt's shadow.

Which brings the story to its live edge. On 29 October 2026 NASA issued a formal request for information, notice 80GSFC27RFIHSTS, asking industry for its capability across three tracks: boost Hubble to a higher orbit — the notice's text targets at least 600 kilometres — service it to improve its capability or resilience, or dispose of it by controlled re-entry. The three tracks are genuinely different futures. A boost is the minimal intervention: it buys altitude and nothing else, and if secondary analyses are right, a successful lift to 600 kilometres or above could add decades of orbital lifetime, after which the instruments, not the orbit, would set the end. Servicing is the ambitious version: new gyroscopes or batteries, perhaps more,

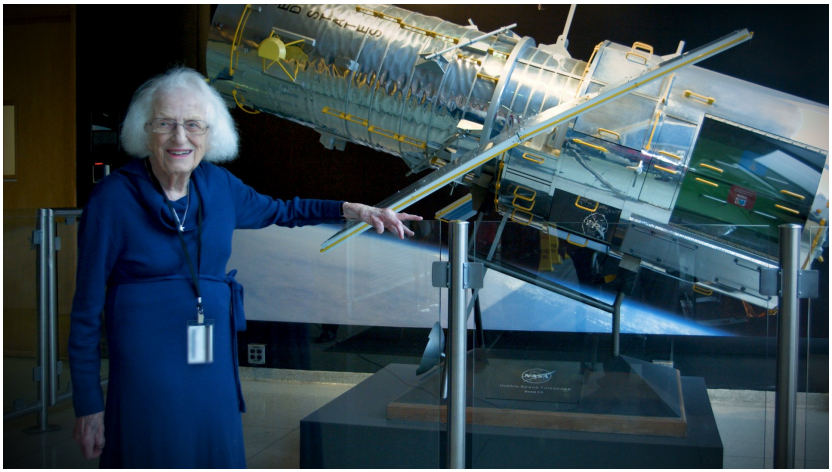
delivered by a vehicle that would have to rendezvous with a telescope never designed for robotic visitors — though the 2009 crew did leave it a soft-capture ring, a docking target fitted precisely so that a future vehicle would have something to hold. Disposal is the sober version: accept the end, and spend the money making it a safe one. NASA is explicit about what this is and is not: an information-gathering exercise only. No provider has been selected, no contract offered, no budget announced. Responses are due at 3 p.m. Eastern on 30 November 2026 — days after this book's snapshot date, and barely a month after the request was issued, a timetable that itself says something about how NASA reads the decay curve. Any mission that results would need to fly by 2032, ahead of the predicted re-entry. Isaacman's framing, in the announcement, was plain: "Hubble still has important science ahead of it… If there are innovative and cost-effective ways to extend the life of an asset already on orbit, we owe it to the American taxpayer and the scientific community to explore them." Associate administrator Nicky Fox added the timing logic: explore a boost now, while the flagship meant to follow Hubble's ultraviolet line — the Habitable Worlds Observatory — is still in development.

Part One therefore ends the way the telescope's own story currently stands: unfinished, on a deadline. As of November 2026, Hubble is observing on one gyroscope, below 500 kilometres, with its discoverers still queueing for its time — and the question of whether anyone will come for it one more time is open, dated, and awaiting answers by 30 November. As of this book's snapshot, no company had publicly declared a response to the request; the first hard fact in the next chapter of this story will be the response list itself, and what it reveals about whether

the commercial space industry believes a 36-year-old telescope is a business case, a responsibility, or both. The telescope, meanwhile, does what it has done through every previous uncertainty in its long life — the flaw, the cancellations, the failures, the rationing. It observes, on schedule, tonight.

Part Two

Chapter 8 — The Namesake



Nancy Grace Roman joined NASA in 1959, six months after the agency was founded, and became its first Chief of Astronomy. For two decades she led the committees, the planning, and the congressional case for a large space telescope. The telescope that case produced was Hubble. The telescope that carries her name launched in 2026. She is the hinge between the two halves of this book.

Credit: NASA

Part One of this book belongs to a telescope. Part Two belongs to another one. This chapter belongs to the person who stands in both.

Nancy Grace Roman was born on 16 May 1925. She took her degree at Swarthmore College in 1946 and her doctorate in astronomy at the University of Chicago in 1949, and in 1959 — six months after the agency itself was founded — she joined NASA. By 1960 she was in post as Chief of Astronomy and Relativity: NASA's first Chief of Astronomy, and its first woman in a leadership position, the first female executive in the

agency's history.

The job she took on was not, at the start, a telescope. It was an argument. Astronomers had been making the case for an observatory above the atmosphere since Lyman Spitzer's paper of 1946, and inside the young agency someone had to convert that case into committees, plans, budgets, and testimony. For the next two decades, that someone was Roman. NASA's own biography describes the work plainly: she led science and planning committees, brought together scientists and engineers, briefed executive branch officials, and lobbied NASA officials for what was then called the Large Space Telescope. When NASA representatives appeared before Congress on the subject, she wrote the testimony. The pitch she used has come down as a quip rather than a transcript, and it deserves to be quoted as she meant it — as a way of making a national instrument sound affordable: for the price of one night at the movies each year, each American would receive fifteen years of exciting discoveries.

Arguments like that are usually remembered as rhetoric. Roman's had engineering consequences. One of them is easy to miss and worth recording: she pushed to get charge-coupled devices — CCDs — installed as the telescope's image sensors, instead of the sensor technology that had been standard before them. The electronic eye that made Hubble's images possible, the eye whose descendants sit in nearly every camera flown since, is there partly because the chief of astronomy insisted on it during the years when the design was still fluid. Institutions remember launch dates. They less often remember who chose the detector.

The machinery she ran can be seen in the programme's paper trail. A National Academy of Sciences report in 1969 endorsed the scientific case for a large space telescope. A first working-group meeting in 1974 settled into concepts, budgets, and technical requirements, with the science side recommending interchangeable instruments working across ultraviolet, visible, and infrared light. In 1975 the European Space Agency joined the project, providing fifteen percent of the funding through an instrument and the solar arrays, in exchange for a guaranteed share of observing time for European astronomers. None of these steps is a discovery. All of them are the substance of institution-building: the slow conversion of a good idea into an international programme with a budget line. That conversion was Roman's daily work for the better part of twenty years, conducted in committee rooms and hearing rooms rather than at a telescope.

Her title deserves a moment of precision, because it is easy to read past. A chief of astronomy at a new agency does not merely advise. The role sat at the junction where scientific priorities became agency plans — where the community's wishes were weighed, sequenced, and defended in front of the officials who controlled the money. To hold that post as the first woman in a leadership position at NASA, in the 1960s, while carrying a programme whose payoff lay decades in the future, required a particular kind of stamina: the willingness to keep making the same correct argument, in improving forms, until the institution was ready to fund it. The pitch about the price of a night at the movies was the public surface of that stamina. Underneath it sat twenty years of committee work that almost nobody outside the agency ever saw.

The campaign took roughly two decades, which is the correct timescale for what she was doing. She was not proposing an instrument; she was building the constituency, the committee record, and the congressional patience that a flagship observatory requires before a single piece of glass is ground. Congress approved funding in 1977. The telescope that resulted was renamed for Edwin Hubble in 1983 and launched in 1990, and it became, after its repair, the most productive observatory of its era. Her colleague Ed Weiler gave her the title the history books kept: the Mother of Hubble.

Roman did not live to see her name go to space. She died on 25 December 2018, aged ninety-three — after Hubble's twenty-eighth year in orbit, and while the agency's next wide-field flagship still existed under its working name, WFIRST, the Wide Field Infrared Survey Telescope.

On 20 May 2020, NASA renamed that mission. Administrator Jim Bridenstine announced that WFIRST would be called the Nancy Grace Roman Space Telescope, and his reason was stated in terms of succession: it was because of Nancy Grace Roman's leadership and vision that NASA became a pioneer in astrophysics and launched Hubble, and he could think of no better name for the successor to NASA's Hubble and Webb telescopes.

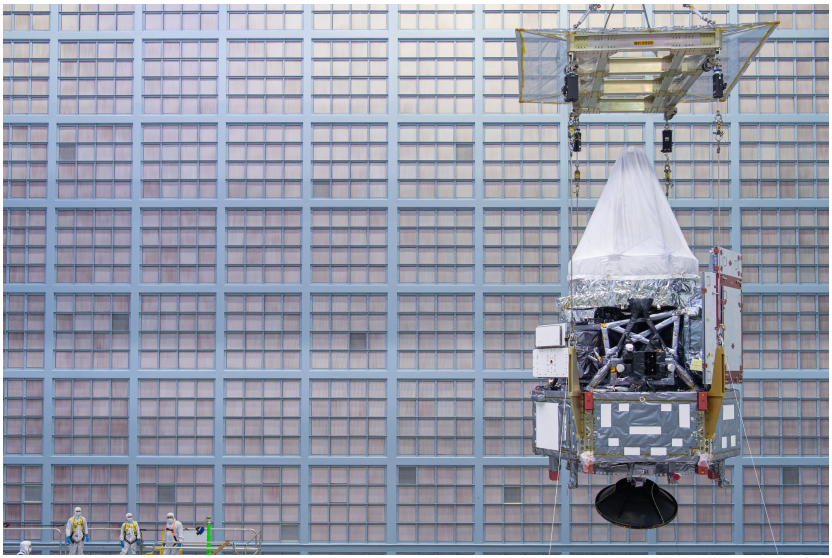
Consider what the naming actually joins. The woman spent twenty years arguing one telescope into existence — a 2.4-metre mirror pointed at small patches of sky with unmatched sharpness. The telescope that carries her name is built around a mirror of exactly the same diameter, 2.4 metres, pointed at patches of sky at least a hundred times wider. She campaigned

for the first. She never saw the second fly; it launched on 30 August 2026, nearly eight years after her death. The two halves of this book are not joined by a theme imposed afterwards. They are joined by a career.

That is why she gets a chapter of her own, placed here, between the elder telescope and the younger one. Everything in Part One happened because the argument she ran for two decades was won. Everything in Part Two happens under her name. The rest of this book is about what the second telescope is, where its mirror came from, and what it is doing right now, a million miles from Earth, with its instruments waking up.

The timing of the naming is part of its meaning. It came in May 2020, two months after NASA approved the mission for implementation — after the design gates, when the telescope had stopped being a study and become a build. Names given at that stage are not aspirations; they are identities the hardware carries through integration, testing, and launch. Roman's name accordingly appears in the record of every milestone that followed: the completed mirror in 2020, the passed design review in 2021, the finished observatory in 2025, and the launch coverage of 30 August 2026, when the agency that she joined in its first year sent her name a million miles from Earth. She had been gone nearly eight years. The argument she spent twenty years winning is, at the time of this book, still producing new chapters.

Chapter 9 — The Gift



The Roman observatory's primary mirror is 2.4 metres across, the same diameter as Hubble's. It began as part of a telescope assembly built for the National Reconnaissance Office and donated to NASA, then was refigured for astronomy at L3Harris in Rochester, New York. The donation was hardware — optics, structures, controllers, and a baffle — not a finished telescope. NASA built the observatory around it.

Credit: NASA/Goddard Space Flight Center/Michael Guinto

Every flagship observatory begins as a line in a survey. Roman began as two.

In 2010, the National Academies' decadal survey *New Worlds, New Horizons* — the astronomy community's once-a-decade ranking of what to build next — named the Wide Field Infrared Survey Telescope, WFIRST, its top-ranked priority for a large space mission. As ranked, WFIRST was a comparatively modest instrument: a near-infrared observatory built around a mirror of

roughly 1.3 to 1.5 metres, designed to survey wide areas of sky in infrared light. It was a plan in search of hardware.

The hardware arrived from an unexpected direction. In January 2011, the National Reconnaissance Office — the agency that builds and operates the United States' reconnaissance satellites — told NASA it had two unneeded telescope optical systems. NASA accepted the offer in August 2011. On 4 June 2012, the donation was announced publicly: NASA had taken ownership of hardware for two telescope assemblies, stored at their manufacturer, ITT Exelis in Rochester, New York, each built around a primary mirror 2.4 metres across — the same diameter as Hubble's.

Precision matters here, because the gift is often described more grandly than it was. NASA did not receive two finished telescopes. What changed hands, as NASA Astrophysics Director Paul Hertz described it in July 2012, was space-qualified optics, support structures, controllers, and a baffle for two systems, plus extra parts. There were no instruments. There was no spacecraft, no electronics suite, no launch. What NASA received was the hardest and most expensive single component of a space telescope — its figured optics, already made — and the obligation to build everything else around them.

One assembly was enough. On 30 May 2013, the NASA Administrator directed that pre-formulation work on WFIRST continue using the donated assets — the programme known as WFIRST-AFTA, the Astrophysics Focused Telescope Assets study — basing the design on one of the two donated assemblies. The decadal survey's modest infrared surveyor was

redesigned around a mirror nearly twice the diameter originally planned, at no cost for the glass itself. That single substitution is the reason the younger telescope in this book has the same-size eye as the elder: not imitation, and not coincidence, but inheritance.

A design needs instruments, and in 2014 the pair was set: the Wide Field Instrument, a wide-field near-infrared camera, and the Coronagraph, an instrument for suppressing a star's light to image the planets around it. Those two — one to survey, one to demonstrate a new way of seeing — remained the payload from that point forward, through every review the mission subsequently passed.

Formalities followed. On 17 February 2016, NASA's Associate Administrator approved WFIRST to begin Phase A — the mission's formal new start. The following day, 18 February 2016, NASA announced that WFIRST had formally transitioned from a study to a project, with an orbit around the Sun–Earth L2 point selected the same month. The dates differ by a day because they record two different steps: the internal approval, then the public announcement.

It is worth pausing on what the donation did to the mission's economics and its politics. The decadal survey had ranked WFIRST first among large missions on the strength of a smaller telescope. A sceptical reader of budgets could ask whether a bigger mirror meant a bigger bill and a longer road. The gift answered part of that question in advance: the single most difficult component — a space-qualified 2.4-metre primary and its assembly hardware — already existed, built and paid for under another programme. What remained was everything else,

and everything else was substantial: a spacecraft, two instruments, a decade of integration and testing, a launch vehicle, and five years of operations. The mission's later cost history belongs to that remainder. When NASA approved WFIRST for implementation on 2 March 2020, the expected development cost was 3.2 billion dollars, with a maximum total cost of 3.934 billion including the Coronagraph and five years of science operations; a replan in June 2021 set the life-cycle cost at 4.316 billion dollars. Those are the honest numbers, and the chapters ahead keep them in view: the glass was a gift, the observatory was not free.

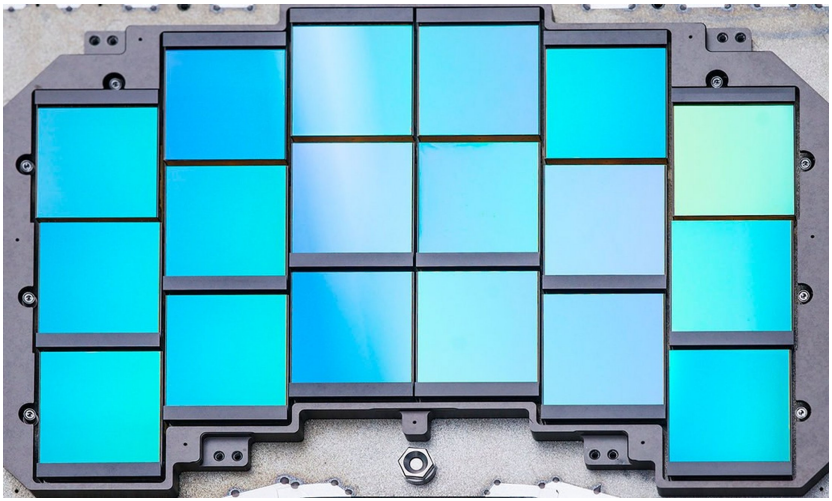
Design maturity had its own gate. On 29 September 2021 the mission passed its Critical Design Review, NASA's formal finding that the design and developmental engineering work was complete and the project could proceed to build in earnest. The build that followed — focal plane, instrument, telescope assembly, payload, spacecraft — is the subject of the next two chapters, and nearly every dated milestone in them descends from the sequence set in motion here: a 2010 ranking, a 2011 offer, a 2012 announcement, a 2013 direction to use the assets, a 2014 instrument pair, and a formal start in February 2016.

The remaining gates can be told briefly, because the chapters after this one take them up in the hardware. NASA approved the mission for implementation on 2 March 2020. On 20 May 2020 it received its permanent name, for the woman in the previous chapter. The life-cycle cost, after a June 2021 replan, stood at 4.316 billion dollars — the figure launch coverage rounds to $4.3 billion. The mirror at the centre of it all, the donated glass, was refigured and modified for its new purpose at L3Harris in Rochester, New York, and completed on 3 September 2020.

Step back and the shape of the thing is unusual. A survey committee asked for a telescope. A spy-satellite agency handed over optics built for another purpose entirely. The mission that resulted carries the name of the administrator who campaigned Hubble into existence, and it flies a mirror the same size as Hubble's because that is the size the donated hardware happened to be. Almost nothing about Roman's origin was planned as a whole. What NASA did, methodically and over fifteen years, was build a coherent observatory out of the parts it had been given — and then fly it ahead of schedule and on budget. The next chapter looks at the machine they built.

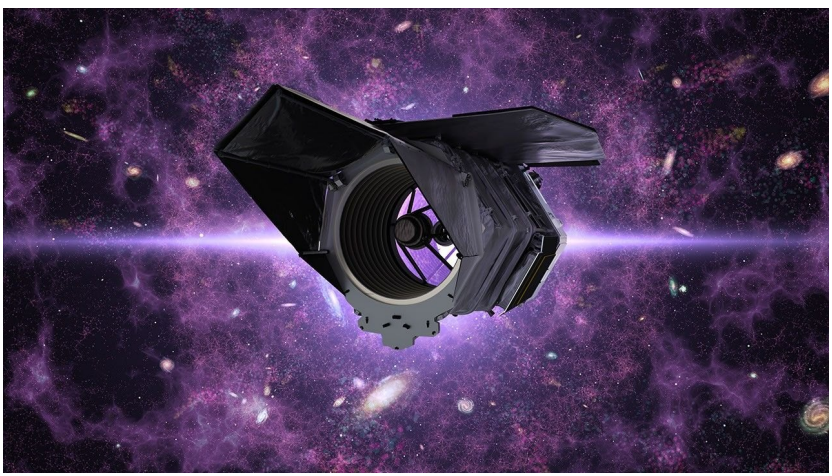
One geographical detail ties the gift together. The assemblies were stored at their manufacturer in Rochester, New York. Decades later, the refiguring of the chosen primary — the work that converted reconnaissance optics into an astronomy mirror finished to Roman's requirements — was also done in Rochester, at L3Harris, and completed on 3 September 2020. Rochester has been an optics city for generations, home to the firms that ground and polished much of America's space glass, reconnaissance and civilian alike. The donated mirror never really left home. It waited in the city that made it, was remade in the city that made it, and left for Maryland and then Florida as the heart of a telescope its builders had never intended it for. The gift, in the end, was not only hardware. It was hardware plus the industrial base that knew what to do with it.

Chapter 10 — The Wide Eye



Roman's Wide Field Instrument is a 300-megapixel camera: eighteen detectors behind a 2.4-metre mirror, covering 0.281 square degrees of sky in one exposure — a field bigger than the full Moon, at least one hundred times wider than Hubble's view, in light from the visible to the near-infrared.

Credit: NASA/Chris Gunn



The artist concept shows the Roman observatory as it is designed to appear at the Sun–Earth L2 point, about a million miles from Earth. It is a simulation, drawn before launch — not a capture from the spacecraft.

Credit: NASA's Goddard Space Flight Center

Start with the mirror, because the mirror is the book's refrain. Roman's primary is 2.4 metres in diameter, exactly Hubble's diameter. The resemblance ends at the rim. Hubble's primary weighs 828 kilograms. Roman's weighs about 410 pounds — roughly 186 kilograms, about eighty percent less, less than a quarter of Hubble's weight for the same collecting area. Between those two numbers sits forty years of optics: the younger mirror was received from another government agency and modified for astronomy, its refiguring completed at L3Harris in Rochester, New York on 3 September 2020. It is one of ten mirrors in the telescope; on 17 April 2024 the full set was combined and the telescope passed its first vision test.

Behind the mirror sits the reason the mirror matters: the Wide Field Instrument, the WFI. NASA describes it publicly as a 300-megapixel camera, and 300 megapixels is the figure this book uses. The array behind the number is eighteen detectors, each a grid of 4,096 by 4,096 pixels, working together as one focal plane. In a single exposure the WFI covers 0.281 square degrees of sky — a patch bigger than the full Moon appears from Earth — across wavelengths from 0.48 to 2.3 micrometres, from visible light into the near-infrared. Eight imaging filters span that range, and the instrument also works as a slitless spectrometer, spreading the light of everything in the field into spectra. Its pixels sample the sky at 0.11 arcseconds each. Set against Hubble, whose sharpness Roman matches, the field of view is the revolution: at least one hundred times larger in a

single frame.

An instrument like that is built, deliberately, over years. The focal plane system — the camera's heart — was completed and delivered on 16 May 2023. The Wide Field Instrument itself was completed on 13 September 2023. In May 2024 the second instrument arrived, and on 12 December 2024 telescope and instruments were integrated together onto the instrument carrier: the payload was complete.

The focal plane itself rewards a closer look. Each of the eighteen detectors holds about 16.8 million pixels; the flight array flies with six spares built alongside it. The detectors do their work cold — an operating temperature near 89.5 kelvin, colder than −180 degrees Celsius — because infrared sensors must be quieter than the faint heat of the sky they measure. The instrument's eight imaging filters divide the 0.48-to-2.3-micrometre range into bands, letting astronomers select the colour of infrared light a survey requires, and a grism and prism turn the same focal plane into a slitless spectrometer: instead of a spectrum of one chosen object, every object in the wide field gets its light spread at once. That is the wide eye's real character. It does not merely photograph more sky per frame; it measures more of what is in the frame — positions, colours, spectra, and, across repeated visits, changes — for everything that falls inside its Moon-sized view.

The second instrument is the Coronagraph, built by the Jet Propulsion Laboratory and delivered to Goddard in May 2024, then integrated onto the instrument carrier that October. Its task is the hardest trick in observational astronomy: block a star's light so completely that the planets beside it — planets as much

as one hundred million times fainter than their star — become visible directly. It does this with masks, deformable mirrors, and control loops that hold the darkness steady. One thing must be said about it exactly as NASA says it: the Coronagraph is a technology demonstration. It is not a survey instrument and it is not expected to work like one. Over roughly three months of preplanned observations spread across the mission's first eighteen months, it is meant to prove techniques that a future observatory — one built to photograph Earth-like planets — will depend on. Judged as a demonstration, even a partial success is a result.

The last component of the wide eye is the one readers never see: the data system. Roman is expected to return about 1.4 terabytes of data a day — some 20,000 terabytes over its five-year prime mission — downlinked at up to 500 megabits per second through ground stations in New Mexico, Australia, and Japan, and delivered into the Mikulski Archive for Space Telescopes, the same public archive that holds Hubble's data. There is no proprietary period. Roman's observations are public from the start, available to any astronomer — and any member of the public — on the same terms.

The scale of that archive deserves one comparison. Hubble's entire public archive, accumulated over thirty-six years, passed 477 terabytes in 2026. Roman, at about 1.4 terabytes a day, returns more than 500 terabytes a year — which is to say, it will exceed the elder telescope's lifetime archive roughly every year it operates, and reach some twenty petabytes across the five-year prime mission. This is not a criticism of the elder instrument; it is the arithmetic of the wide eye. A camera that photographs a Moon-sized field at Hubble sharpness, night after night for

years, cannot help producing a flood. The mission was designed around the flood: downlink rates up to 500 megabits per second, the highest of any NASA astrophysics mission, and an archive built to serve the data to the world rather than to a fortunate few.

The telescope assembly around the instruments completes the picture. The Optical Telescope Assembly — the primary, nine additional mirrors, and their structures and electronics — was delivered to Goddard's largest clean room on 7 November 2024, the final major delivery of the build. A telescope, in other words, of ten mirrors in all: two inherited in concept, all ten aligned as one eye, tested as one eye in April 2024, and flown as one eye in 2026. It is a point worth keeping for the chapters ahead: every Roman image, from the first blurred test frame to the surveys of the next decade, comes through all ten of those mirrors acting as one.

Hold the machine together in one view and its character is plain. The same-size eye as Hubble, at a fifth of the mirror's weight. A camera that takes in a Moon-sized field at Hubble sharpness. A demonstrator learning to photograph planets directly. And an archive that gives everything away. What such a machine is *for* is the subject of the chapter after next. First, it had to leave the ground.

Chapter 11 — Launch, and First Photons



A Falcon Heavy lifts the Roman observatory off Launch Complex 39A at 7:26 in the morning, Eastern time, on 30 August 2026. Thirty-one minutes later the observatory separated and was flying on its own.

Credit: NASA/Joel Kowsky



The Roman launch from a second vantage, the twin side boosters that would return to land in Florida.

Credit: NASA/John Kraus

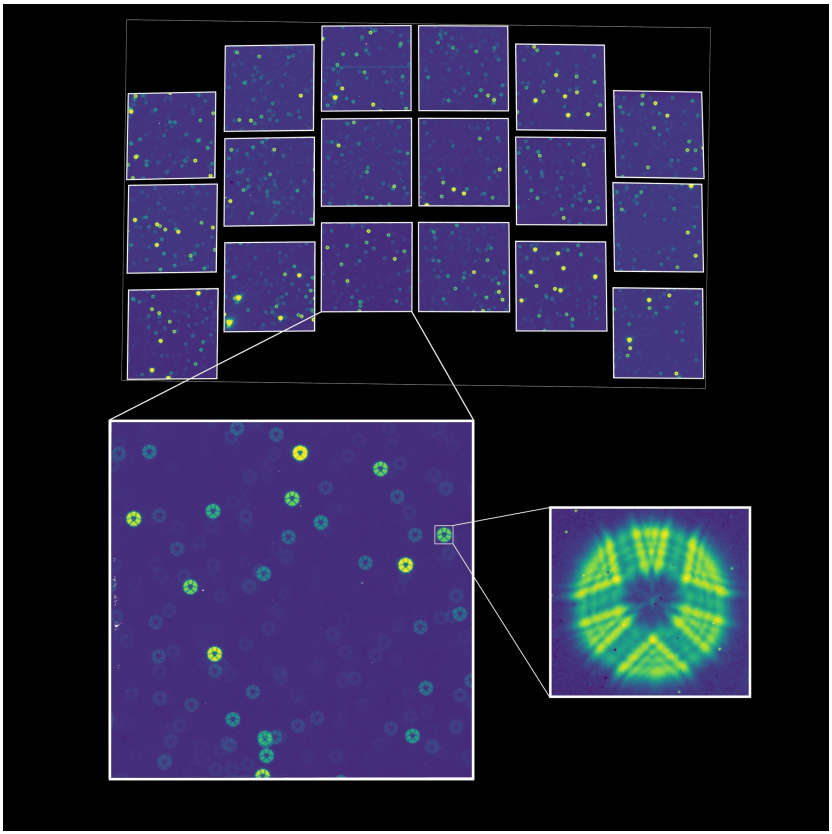
The observatory was finished on the ground before it was finished in fact, and the order of those events is worth keeping straight. On 25 November 2025, technicians joined Roman's

inner and outer portions in the largest clean room at NASA's Goddard Space Flight Center, and the observatory was structurally complete; NASA announced the completion on 4 December. The testing that followed was not a formality. In March 2026 the full observatory was blasted with extreme sound, shaken, and subjected to electromagnetic-interference testing, and passed all three. In May 2026 came the final ground deployment tests of the solar array and the aperture cover. In June 2026 the observatory was shipped to Kennedy Space Center, arriving on 21 June.

On 30 August 2026, at 7:26 a.m. Eastern Daylight Time, a SpaceX Falcon Heavy lifted off from Launch Complex 39A at Kennedy Space Center with Roman aboard. NASA's administrator described the mission at launch as delivered ahead of schedule and on budget — on budget, the agency was careful to say, not under it. Communications were acquired seven minutes after liftoff. At 7:57 a.m., thirty-one minutes in, Roman separated from the rocket's second stage and was flying on its own; the two side boosters landed back in Florida. In the minutes after separation Roman deployed its Solar Array Sun Shield, swinging four outer panels into place to complete a six-panel array, and the solar panels and lower instrument sun shade were confirmed deployed about eighty-three minutes after liftoff.

Then the telescope unfolded itself, step by dated step. On 31 August, a first mid-course correction burn of about three minutes adjusted its trajectory toward its final orbit, and that afternoon the high-gain antenna — a carbon-composite dish 5.6 feet wide — completed its deployment, the link that would carry the data home. On 1 September the Deployable Aperture Cover,

the visor that shades the telescope's mouth, swung open on three booms; that was the final physical deployment. The same morning, the Coronagraph Instrument was powered on for the first time. On 11 September the Wide Field Instrument began cooling toward operating temperature, its eighteen detectors were activated, and calibration data followed. Between 7 and 17 September the three ground stations that will receive Roman's data — in Japan, New Mexico, and Australia — were tested and confirmed ready.



Roman's first photons, recorded by the Wide Field Instrument in September 2026, are an engineering test frame: a sea of out-of-focus stars, each one a ring of light, taken before the telescope reached best focus. The frame's job

was to prove the camera was alive. It is not a science image, and this book does not present it as one.

Credit: NASA's Goddard Space Flight Center, Tyler Desjardins (STScI)

What the instruments saw first must be described with care, because these were engineering test frames, not science images. The Wide Field Instrument's first photons, published with NASA's 15 September update, show a sea of out-of-focus stars: rings — donuts — of light, taken while the detector array was still configured as it had been for launch and far from best focus. Their purpose was proof of life, and they provided it. The Coronagraph took its first test observation of cosmic light on 22 September, a faint star in the Large Magellanic Cloud through a still-warm detector, and a second on 27 September with the detector cooled, recording many stars in that galaxy and confirming the pointing. In October the Wide Field Instrument's focus was sharpened by moving the secondary mirror a fraction of a hair's width, and its measured optical quality came in nearly thirty percent better than predicted. On 22 October 2026, NASA announced that Roman had completed its comprehensive checkout, was fully functional, and had entered the science commissioning phase.

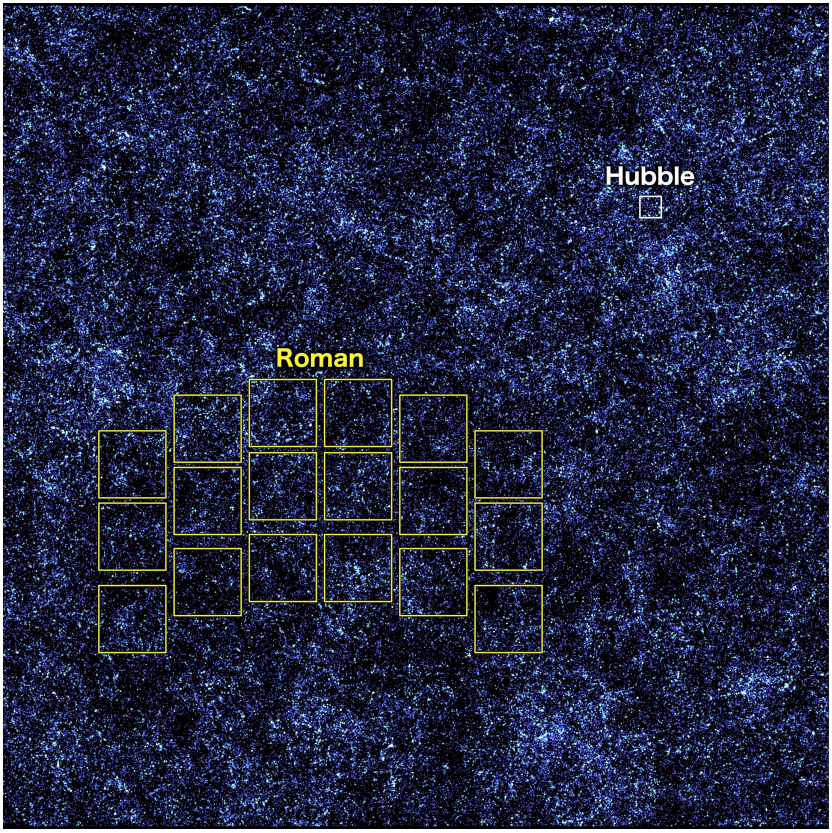
The Coronagraph had its own parallel awakening. Woken on 1 September, it spent its first weeks in a thirty-day decontamination period, held near room temperature — about 22 degrees Celsius — while the main camera went cold around it. NASA's mid-September update recorded a first test of its deformable-mirror "limbs," the actuators that will one day hold a star's light cancelled to a hundred-millionth. Its first observations of cosmic light followed on 22 and 27 September, described in the previous paragraph — faint stars in the Large

Magellanic Cloud, chosen because that galaxy's crowded fields make a strict test of pointing. By mid-October its focus had been corrected as well, with a demonstration of the deformable mirrors planned for the weeks after. A technology demonstration earns its name in exactly this way: not in one announcement, but in a sequence of small, checked, dated successes.

The checkout had a texture worth recording, because it shows what commissioning actually consists of. Before the Wide Field Instrument could open its eyes, it spent about ten days in a controlled warm-up — a decontamination bake near −65 degrees Celsius — before cooling in stages: the heaters off on 11 September, the detectors brought down past −140 degrees on the way to a final operating temperature near −183 degrees, and the eighteen detectors activated as the cold arrived. The first calibration data came that night and the first test data the next morning; over the following weekend the filter wheel turned for the first time in zero gravity and the focus mechanism moved. The fine guidance sensors were tested between 15 and 21 September and held the telescope's pointing steadier than a ten-thousandth of a degree — stability NASA illustrated as holding a view steady on a dime a hundred and fifty miles away, for half an hour at a time with the main camera and eight hours with the Coronagraph. When the focus was sharpened in October, the secondary mirror was moved by about one sixteenth of the diameter of a human hair, and the camera's measured optical error came in at 63 nanometres against a requirement of about 90 — nearly thirty percent better than predicted. None of this is spectacle. All of it is the difference between a spacecraft and an observatory.

Two facts close the chapter, and this book states them plainly. First, Roman has not yet arrived. Its orbit insertion at the Sun–Earth L2 point, about a million miles from Earth, is expected roughly one hundred days after launch — early December 2026. Second, no Roman science images exist yet. Everything published so far is launch photography, clean-room photography, and engineering test frames. The first science images are expected by early 2027, on NASA's written schedule. A book about what telescopes capture has to be honest about a telescope that has not yet begun to capture — and the honesty is easy, because the waiting is now measured in weeks.

Chapter 12 — The Census to Come



A simulated Roman survey field: more than a billion galaxies are expected across the mission's wide-area surveys, each one measured to the same standard, so that the distortions of their shapes and the pattern of their clustering can be counted as data. The image is a simulation, generated before launch from models — Roman's own census frames are still to come.

Credit: NASA's Goddard Space Flight Center and A. Yung

Hubble's method, across thirty-six years, has been the portrait. An astronomer proposes a target; the telescope stares; the result

is one field studied in depth — a nebula, a cluster, a patch of apparently empty sky that turns out to hold thousands of galaxies. Roman's method is the opposite: the census. Instead of choosing targets one at a time, it will photograph enormous areas of sky to the same depth and the same standard, and count what is there. Its surveys are designed to record more than a billion galaxies. The difference is not scale alone. A portrait answers questions about an object. A census answers questions about a population — and the largest open questions in cosmology are population questions.

The first of them is the expansion of the universe. Part One told how two supernova teams found the expansion accelerating in 1998, how Hubble then traced dark energy's history, and how the local and early-universe measurements of the expansion rate still disagree. Roman attacks the problem as a census-taker. Its High Latitude Wide Area Survey will map the shapes of galaxies across a vast area — the technique called weak gravitational lensing, in which the gravity of intervening dark matter slightly distorts each galaxy's image, so that counting distortions across millions of galaxies draws a map of the dark matter itself — together with the clustering of those galaxies in three dimensions. Its High Latitude Time Domain Survey will watch fields repeatedly to catch Type Ia supernovae, the same class of exploding star that revealed the acceleration, but in numbers and at distances no targeted programme could assemble. Dark energy and dark matter are, between them, most of the universe. Hubble showed they were there. Roman will measure them by enumeration.

The second census is of planets. From its station at L2, Roman will stare at the crowded star fields toward the centre of our

galaxy, watching for microlensing events — the brief brightening of a background star when a foreground star, and any planets around it, pass in front and bend its light. The Galactic Bulge Time Domain Survey is expected to find more than a thousand wide-orbit planets this way: planets on orbits like the outer planets of our own system, a population other methods barely reach. The same data should record more than a hundred thousand planets crossing the faces of their stars. Microlensing has a particular virtue a census needs — it is indifferent to how faint the host star is, so it counts planets as they are, not as the bright and easy cases present them.

The third task is the Coronagraph's, and it is deliberately the smallest. Across roughly three months of observations in the mission's first eighteen months, the demonstration instrument will image planets directly — worlds up to a hundred million times fainter than their stars — not to complete a survey but to prove the techniques on which a future observatory, built to photograph Earth-like planets, will stand. It is pathfinding, labelled as such.

The census method changes the sociology of the science as well as its statistics. A targeted observatory allocates its time proposal by proposal, and the sky it photographs is the sum of what individual teams thought to ask for. A survey observatory commits its fields in advance, observes them to a uniform standard, and releases everything into a public archive with no proprietary period. Roman's prime mission is expected to produce on the order of twenty petabytes of archived data — a collection so large that a substantial share of Roman science will be done by people who never proposed for a minute of its time, working on fields chosen before the telescope launched.

Hubble's archive demonstrated the value of that model across thirty-six years, including discoveries made in data years after it was taken. Roman is built to make the archive the main event from the first day: the surveys are the mission, and the mission's product is a counted sky that anyone may use.

There is a second, quieter consequence. Because the wide-area, time-domain, and bulge surveys measure the universe by several independent methods at once — lensing distortions, galaxy clustering, supernova distances, stellar microlensing — their results can be checked against each other inside a single instrument's calibration. The disagreement between the local and early-universe expansion rates, which Part One left open, is exactly the kind of question such cross-checks exist to settle: not by one heroic measurement, but by several ordinary ones that cannot all be wrong in the same direction.

How long will the census run? The prime mission is five years. The observatory was designed for a five-year extension beyond that, and its fuel was budgeted on that ten-year basis. In September 2026, NASA reported that precise flying had saved so much propellant that the tanks hold fuel for at least twenty-two years of potential operations. That figure needs its label kept on: it is a fuel projection, not an approved mission life. No extension has been granted; what exists is a five-year mission, a designed path to ten, and enough fuel, in principle, for much longer. This book reports all three numbers as what they are.

None of this replaces the elder telescope's trade, and the book's pairing depends on keeping the two distinct. A census establishes what exists and in what proportions; it cannot, by

itself, take the ultraviolet spectrum of one interesting galaxy, or stare at one gravitational lens until its structure resolves, or return to one nebula across nineteen years to watch a jet lengthen. Those are portraitist's jobs, and they remain Hubble's — in wavelengths Roman does not even carry. The expected pattern of the next decade is therefore not succession but referral: the census finds the classes, the extremes, and the anomalies; the portraitists — Hubble while it lasts, and targeted instruments after it — take the close-ups. Roman's billion galaxies are, among other things, a finding list for every other telescope of its era.

When does it start? Roman enters its surveys after commissioning at L2, and NASA's written sources put the first science images by early 2027. Until those frames exist, every statement in this chapter is a statement about a designed capability, and the book has kept them in that tense on purpose. Hubble finds and characterises; Roman censuses. The elder telescope is still working its portraits, one gyro and all, while the younger one cools and focuses a million miles out — and the census, when it begins, will be the largest count of the sky ever taken with a single instrument.

Closing — The Mirror, Twice

— The Mirror, Twice



Two mirrors, one diameter. Hubble's 2.4-metre primary was the product of a 1970s budget compromise; Roman's 2.4-metre primary was inherited hardware, donated and refigured. At roughly a fifth of the elder mirror's weight, and feeding a camera with a field at least one hundred times wider, the younger mirror is the measure of what forty years changed — and what it did not. A woman who never flew argued the first of these telescopes into existence and lent her name to the second. The same glass, worked twice, thirty-six years apart, is still pointed outward — one eye near home and failing gracefully, one eye a million miles out and just opening. Between them they have not finished. Judging by every deeper field either has ever taken, neither has the sky. No end in sight.

Credit: NASA (Hubble mirror, left); NASA/Chris Gunn (Roman mirror, right)

Everything in this book reduces, in the end, to a single measurement repeated twice: 2.4 metres.

The first time, the number was a compromise. The Large Space Telescope was drawn at three metres and cut down under budget pressure in the 1970s, and the mirror that resulted — ground in Danbury, polished superbly to a figure wrong by about two micrometres — launched in 1990, was corrected by astronauts in 1993, and has been working since. The second time, the number was an inheritance. A reconnaissance programme built

telescope assemblies around 2.4-metre mirrors, found it did not need them, and gave the hardware to NASA; one of those mirrors, refigured and lightened by forty years of progress to about a fifth of the elder mirror's weight, launched in 2026.

Same diameter. Nearly everything else inverted. Hubble looks at small pieces of sky with unmatched sharpness, in ultraviolet, visible, and near-infrared light. Roman takes in a field at least one hundred times larger at comparable sharpness, in visible and near-infrared light, and surveys where Hubble samples. Hubble's data filled a great public archive across thirty-six years; Roman returns more data in a day than many observatories manage in a year, and gives it away immediately. Hubble was serviced by hand, five times, by astronauts. Roman is beyond any hand's reach at L2 and must simply work.

Longevity tells the same double story. Hubble was designed for a fifteen-year mission; it is past thirty-six years, kept alive first by astronaut servicing and then by ground-side ingenuity, rationing gyroscopes and accepting narrower skies to buy time. Roman is designed for five years with a built path to ten, carries fuel that could in principle last far longer, and will never be touched again by human hands — whatever it becomes in its second decade, it becomes on its own. The elder telescope's life was extended by repair. The younger one's can only be extended by margin: by everything its builders put in reserve before it left. Both are, in their different ways, arguments that a telescope's working life is decided less by its launch day than by the care taken before and after it.

And the division of labour between them is not a handover but a partnership with one clear asymmetry. Roman has no ultraviolet

capability, and neither does Webb. The hottest and most violent light in the universe — young massive stars, gas falling toward black holes, the thin medium between galaxies — is still Hubble's alone to record, and no successor with comparable ultraviolet capability is expected before the proposed observatories of the 2040s. The elder telescope is not keeping a seat warm. It is holding a wavelength range that closes when it closes.

Even the names make the pairing. One telescope is named for an astronomer — the man whose observations established that the universe expands. The other is named for an administrator — the woman who established that the first telescope would exist. Science remembers its discoverers by reflex and its institution-builders by effort. That both kinds of name now ride on the same size of glass, pointed at the same sky, is the closest thing this subject has to a complete sentence about how astronomy actually gets done: someone finds, and someone makes the finding possible, and the mirror does not care which name it carries.

The book therefore ends, as it was written, with two open endings. One belongs to Hubble: falling slowly from below five hundred kilometres, its predicted re-entry in 2033–34, and a formal question now in front of the commercial space industry — boost it, service it, or dispose of it — with responses due on 30 November 2026 and any rescue required to fly by 2032. The other belongs to Roman: commissioning under way, an orbit insertion expected in early December 2026, and first science images expected by early 2027, when the census begins and this book's second half turns from capability into record. Both endings will have moved by the time many readers reach this

page. That is stated in the snapshot statement, and it is the honest condition of a book about instruments that are still working.

Back Matter

The Snapshot Statement

This book is a snapshot, and it says so on purpose.

Everything in it describes matters as they stood in **November 2026**. At that date: the Hubble Space Telescope was in its thirty-seventh year in orbit, conducting science in one-gyroscope mode, its orbit decayed to below 500 kilometres, with a predicted re-entry in 2033–34 and a NASA Request for Information on commercial boost, servicing, or disposal open for responses until 30 November 2026. The Nancy Grace Roman Space Telescope had launched on 30 August 2026, had completed its comprehensive checkout, and had entered science commissioning while cruising to the Sun–Earth L2 point, with orbit insertion expected in early December 2026 and its first science images expected by early 2027. No Roman science images existed at the time of writing, and none is presented in this book as existing.

Telescope status changes faster than books do. Later printings and the free site editions of this book are updated in place as the record changes, and each updated edition carries a version line and a date. Where an edition and the sky disagree, the sky is right — check the version line, and check the missions' own pages.

Sources

Compiled from the research reports prepared for this book (November 2026), drawing on the makers' and archives' own

publications. Principal sources:

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- NASA Goddard, *The Hubble Program — Timeline*; *Hubble Technology — Summary*
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- STScI releases and plate records for the Hubble Deep Field, Ultra Deep Field, eXtreme Deep Field, and Legacy Field
- STScI, Roman Research Nexus / MAST archive announcements (2026)

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- NASA, Roman mission pages: *Timeline*; *Building Roman*; *Roman Launch*; *Frequently Asked Questions*; *Wide Field Instrument — Technical*, science.nasa.gov
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- NASA news release, *NASA Telescope Named for "Mother of Hubble" Nancy Grace Roman* (20 May 2020)
- NASA, *Roman Space Telescope* illustrations and image galleries (artist concepts are credited as such wherever used)

U.S. Government Accountability Office

- GAO-26-108556 (July 2026) — Roman life-cycle cost and schedule record

Plate imagery was drawn from the official archives listed above. NASA media terms and ESA/Hubble's Creative Commons Attribution 4.0 terms for post-2008 material were applied plate by plate; see Plate Credits.

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Plate Credits

- Pillars of Creation — original (1995) — Jeff Hester and Paul Scowen (Arizona State University), and NASA/ESA
- Pillars of Creation — revisit (2014) — NASA, ESA/Hubble and the Hubble Heritage Team
- Hubble Deep Field (1995) — Robert Williams and the Hubble Deep Field Team and NASA
- Hubble Ultra Deep Field (2004) — NASA, ESA, and S. Beckwith (STScI) and the HUDF Team
- Hubble eXtreme Deep Field (2012) — NASA, ESA, G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University), and the HUDF09 Team
- Hubble Legacy Field (2019) — NASA, ESA, and G. Illingworth (University of California, Santa Cruz; UCO/Lick

Observatory)

- Veil Nebula (2015) — NASA, ESA, Hubble Heritage Team
- Antennae Galaxies (2013) — ESA/Hubble & NASA
- Frontier Fields — Abell 2744 (2014) — NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)
- Eagle Nebula tower (2005) — NASA, ESA, and The Hubble Heritage Team (STScI/AURA)
- Nancy Grace Roman at NASA — NASA
- The Roman observatory in the Goddard clean room — NASA/Goddard Space Flight Center/Michael Guinto
- The Wide Field Instrument and payload integration — NASA/Chris Gunn
- Artist concept — Roman at Sun–Earth L2 (simulation) — NASA's Goddard Space Flight Center
- Roman launches, 30 August 2026 — NASA/Joel Kowsky
- Roman launches — second vantage — NASA/John Kraus
- WFI first-photons engineering test frame — NASA's Goddard Space Flight Center, Tyler Desjardins (STScI)
- Simulated Roman wide-field survey view (simulation) — NASA's Goddard Space Flight Center and A. Yung
- The two mirrors — Hubble's and Roman's — NASA (Hubble mirror, left); NASA/Chris Gunn (Roman mirror, right)
- Cover image — Pillars of Creation, revisit (2014): NASA, ESA/Hubble and the Hubble Heritage Team

About the Plates

This is a visual book, and the plates carry half the telling. Part One is built from Hubble's signature images, taken from the official archives at the highest resolution the archives publish: the Pillars of Creation in both their 1995 and 2014 versions, set at the same scale so the servicing story is visible in the sharpness difference; the deep fields in sequence — Deep Field, Ultra Deep Field, eXtreme Deep Field, and the Legacy Field that contains them — so the reader can watch one telescope stare at nearly the same nothing for thirty years and count what accumulates; and the Veil, the Antennae, the Eagle tower, and the lensing cluster Abell 2744.

Two famous Hubble panoramas were considered and left out on rights grounds, and the book says so rather than slipping them in. The 2007 Carina Nebula panorama and the 2003 Helix Nebula image both blend Hubble data with ground-based telescope data carrying third-party rights outside the archives' blanket permissions; neither could be cleared cleanly for this use, so neither appears. The star-forming-nebula story is carried by the Eagle Nebula plates — the Pillars in both versions, and the tower — and the dying-star story by the Veil, the shrapnel of an exploded star, Hubble data only.

Part Two's pictures are of a different kind, because in November 2026 they can only be of a different kind. Roman has produced no science images yet, and none is presented here as one. What the book shows instead is the record that exists: Goddard clean-room photography of the observatory being built, launch photography from Kennedy Space Center, and the Wide Field

Instrument's first-photons engineering test frame — a sea of out-of-focus stars, each a ring of light, captioned as the test frame it is. Artist concepts and the simulated survey view are captioned as simulations wherever they appear. The closing diptych sets the book's two primary mirrors side by side: Hubble's, from its Perkin-Elmer era, and Roman's, at L3Harris — the same 2.4 metres, worked forty years apart.

Every plate's full official credit line, copied from the archive the file was actually downloaded from, is printed in the Plate Credits at the back of the book, and a short form stands under each plate where it appears.

About the Author

Douglas J. Brownfield is an independent builder and artist based in America. The author writes plain-language books about the tools of the present moment — what they are, what they are for, and how to tell one from another — working from primary sources and dating every claim that can go stale.

This book began with a rhyme the author could not put down: two great observatories, thirty-six years apart, built around mirrors of exactly the same diameter — one of them named for the astronomer who found the universe expanding, the other for the administrator who argued the first one into existence. The author is an enthusiast for both telescopes, and wrote the book to hold the pairing in one place: what the elder has captured across thirty-six years, what the younger is built to capture next, and the woman who joins them.

The author's other books stand on the same shelf rule: one subject, primary sources, no drama framing — the facts at the strength the evidence supports, and the open questions left open and labelled.

Also by Douglas J. Brownfield

Words to Prompt AI Well With — a beginner-friendly field guide to asking AI better questions and getting better answers.

Before Q-Day — how to prepare your Bitcoin and crypto for the quantum change: what's settled, what's coming, and what to

do in the meantime.

What Kind of AI Is That? — the types of AI models, what each kind does, and how to tell them apart.