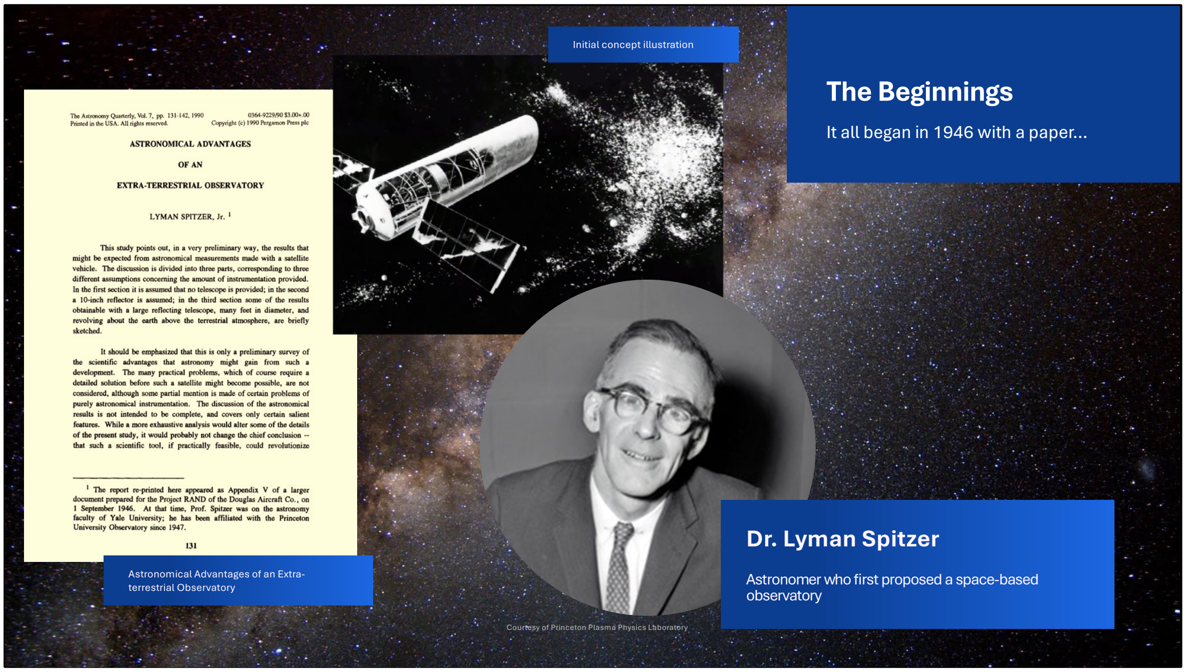
Throughout the history of science, revolutionary instruments propel our understanding with their landmark discoveries. NASA's Hubble Space Telescope is a testament to that concept. Its design, technology and serviceability have made it one of NASA's most transformative observatories. From determining the atmospheric composition of planets around other stars to discovering dark energy, and from verifying supermassive black holes to studying galaxies back near the beginning of time, Hubble has changed humanity's understanding of the universe.

The Hubble Space Telescope began its groundbreaking mission in 1990, forever changing our view of the cosmos and our appreciation of our place within it. Thirty-five years later, Hubble's images and science continue to inspire. This presentation will provide a brief history of the telescope, give an overview of the spacecraft's design, supply a summary of the space shuttle servicing missions, present highlights of its incredible scientific discoveries, and discuss its future.

FOR MORE INFORMATION:
The Hubble Space Telescope –
https://science.nasa.gov/mission/hubble


THE STORY
History
Launch
HP Tau, HP Tau G2, and HP Tau G3



Seventy-five years ago, astronomer Lyman Spitzer envisioned a future for space exploration that deepened humanity's curiosity about the cosmos. A visionary behind the Hubble Space Telescope, Spitzer was among the earliest astronomers pioneering a revolutionary way to explore the universe through astronomical satellites. His vision came over a decade before the launch of the first satellite, Sputnik, as well as the establishment of NASA itself. While the fundamental concept of sending a large telescope into space wasn't new, the reality of doing so was.

With the publication of his famed paper in 1946, "Astronomical Advantages of an Extra-terrestrial Observatory," Spitzer explored the benefits and feasibility of launching a large reflecting telescope into orbit around our planet. He wrote that by operating above Earth's atmosphere, space telescopes would have greater access to wavelengths of light not visible from the ground. They could also take higher quality images.

As noted by Spitzer in his report, the primary contribution of orbital astronomical observatories would be to enable humanity to explore beyond our frontier of knowledge; "not to supplement our present ideas of the universe we live in, but rather to uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time."

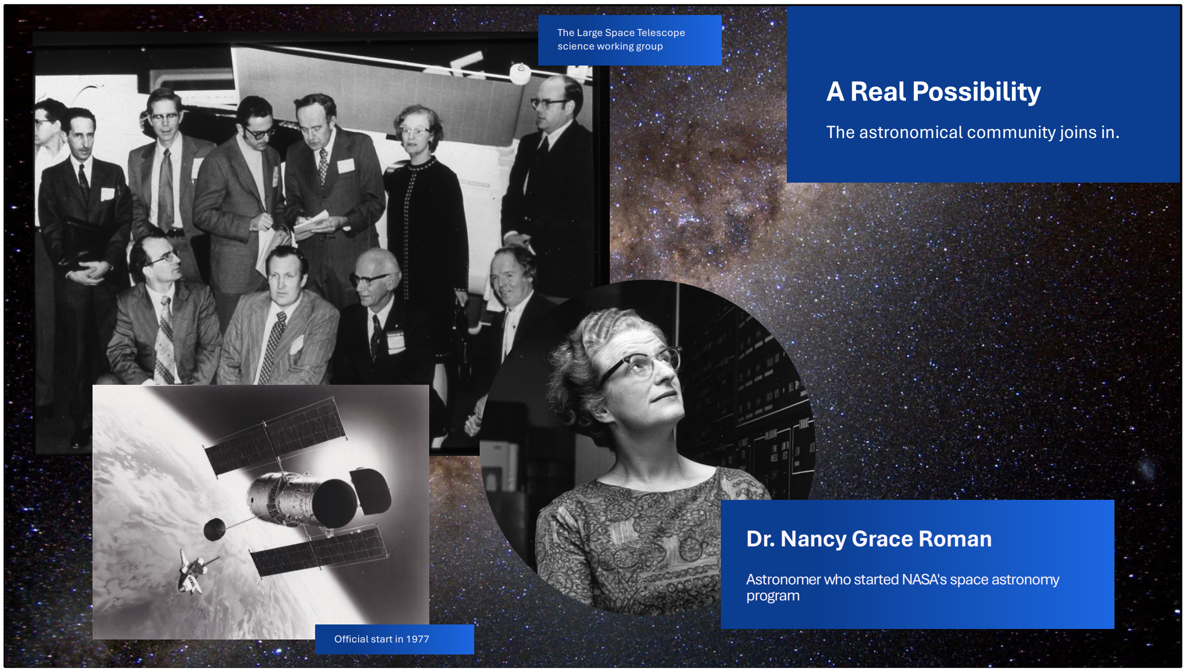
IMAGE:
Spacecraft image is an early space telescope concept by NASA.

FOR MORE INFORMATION:

Lyman Spitzer –
https://science.nasa.gov/people/lyman-spitzer-making-space-for-hubble/

The History of Hubble –
https://science.nasa.gov/mission/hubble/overview/the-history-of-hubble/

Report to Project RAND: Astronomical Advantages of an Extra-terrestrial Observatory –
https://science.nasa.gov/file-detail/astronomical-advantages-of-an-extra-terrestrial-observatory/



NASA formed following the launch of the Soviet satellite Sputnik in 1957. In 1959, an employee at the fledgling NASA asked Nancy Grace Roman, an astrophysicist, if she knew someone who might be interested in creating a space-based astronomy program. She volunteered herself, and NASA hired her only six months after the agency's formation. By 1960, Roman was serving as NASA's Chief of Astronomy and Relativity. Over the next two decades, Roman devoted herself to the cause of securing congressional approval and funding for a Large Space Telescope.

Early on, NASA successfully launched two Orbital Astronomical Observatories (OAOs), placing them in orbit. They made a number of ultraviolet observations and provided learning experiences for the manufacture and launch of future space observatories.

Meanwhile, scientific, governmental, and industrial groups planned the next step beyond the OAO program. Spitzer gathered the support of other astronomers with the help of colleague John Bahcall for a "large orbital telescope" and addressed the concerns of its critics. In 1969, the National Academy of Sciences gave its approval for the Large Space Telescope (LST) project, and the hearings and feasibility studies continued.

After Neil Armstrong's "giant leap for mankind" on the Moon in 1969, funding for NASA space programs began to dwindle, putting the Large Space Telescope program in jeopardy. Planners had to design the telescope under budget constraints. A number of downsizing measures were considered, such as decreasing the size of the primary mirror, the number of scientific instruments, or the number of spare parts created and tests performed. Ultimately, the size of the main mirror was reduced from 120 inches to 94.

In 1974, the Large Space Telescope Science Working Group recommended the space telescope carry a large complement of interchangeable instruments. The requirements for these instruments were to resolve at least one-tenth of an arcsecond (or 1/36,000 of a degree of arc across the sky), and have a wavelength range from ultraviolet through visible to infrared light.

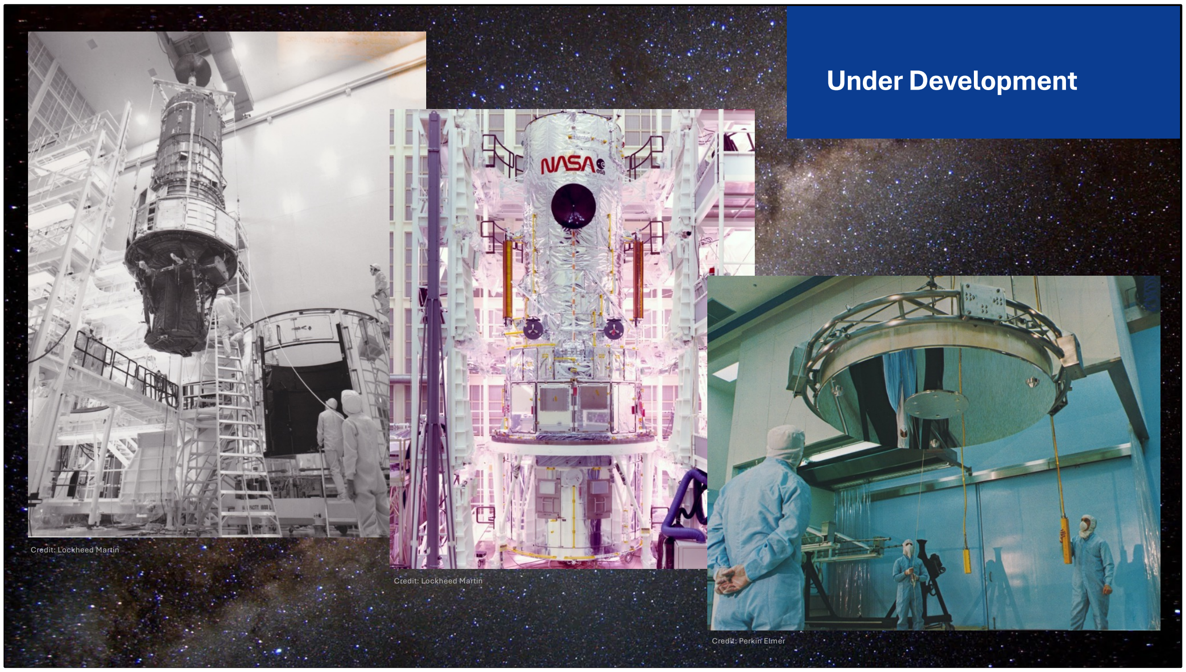
NASA and its industrial partners – called contractors – brought up the option of developing a vehicle that could achieve orbit, return to Earth intact, and be reused repeatedly; the concept of the space shuttle was born. The space shuttle could deploy the Large Space Telescope into space and reel it back for return to Earth. In turn, the telescope's designers created the telescope to fit snugly inside the shuttle's cargo bay.

NASA proposed that the lifetime of the space telescope be 15 years, which implied that the instruments needed replacing periodically on the ground or even in orbit. Scientists had to balance the size and quantity of scientific instruments versus their cost. Too many instruments meant financial support was less likely, but instruments with lesser capabilities would lose scientific support for the telescope. The European Space Agency (ESA) joined the project in 1975 and provided 15 percent of the funding of the Large Space Telescope via contribution of the Faint Object Camera and the solar arrays. In return, NASA guaranteed at least 15 percent of telescope time – the amount of time astronomers use the telescope for space observations – to European astronomers. In 1977, Congress approved funding to build one of the most sophisticated satellites ever constructed.

Later it would be named the Hubble Space Telescope after astronomer Edwin Hubble.

IMAGE:
The Large Space Telescope science working group (John Bahcall standing third from left, and Nancy Grace Roman standing fifth from left)

FOR MORE INFORMATION:
The History of Hubble –
https://science.nasa.gov/mission/hubble/overview/the-history-of-hubble/
Lyman Spitzer –
https://science.nasa.gov/people/lyman-spitzer-making-space-for-hubble/
Nancy Grace Roman –
https://science.nasa.gov/people/nancy-grace-roman-for-hubble/
John Bahcall -
https://science.nasa.gov/people/john-bahcall/
Edwin Hubble –
https://science.nasa.gov/people/edwin-hubble/



With its official approval, development began!

NASA chose Marshall Space Flight Center (MSFC) in Huntsville, Alabama, as the lead NASA field center for the design, development, and construction of the space telescope. Marshall delegated Perkin-Elmer Corporation (now Hughes Danbury Optical Systems) the task of developing the Optical Telescope Assembly and the Fine Guidance Sensors. MSFC selected Lockheed Missiles and Space Company (now Lockheed Martin) to build the spacecraft's outer structure and Support Systems Module (the internal support systems, which includes the computer, power, communications, pointing and control systems), and then assemble the telescope together.

NASA chose Goddard Space Flight Center in Greenbelt, Maryland, to be the lead in scientific instrument design and ground control for the space observatory. Scientists were organized into "Instrument Definition Teams," which would translate scientific aims into scientific devices and incorporate them into the space telescope housing. After an announcement was made to the astronomy community, proposals were received and judged, and five devices were selected as the initial instruments that would be aboard the space telescope: the Faint Object Camera, the Wide Field/Planetary Camera, the Faint Object Spectrograph, the High Resolution Spectrograph, and the High Speed Photometer.

The Johnson Space Center in Houston, Texas, and the Kennedy Space Center in Florida supplied space shuttle support. In all, dozens of contractors, a handful of universities, and several NASA centers, spanning 21 states and 12 other countries worldwide, made the dream of a telescope in space a reality.

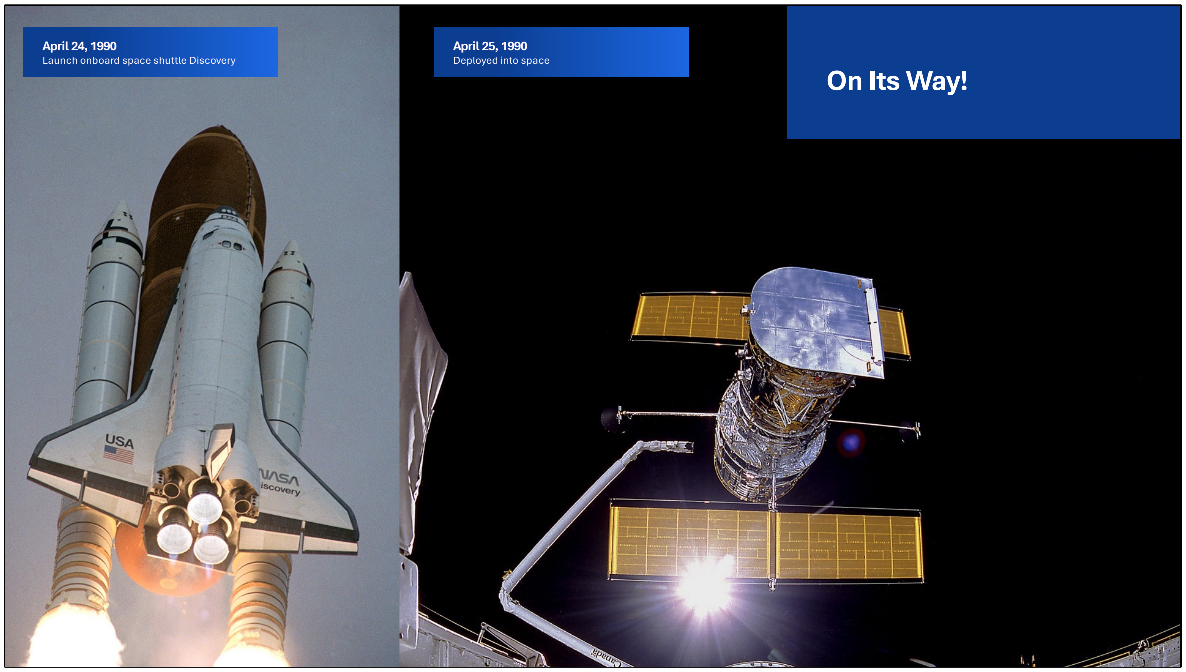
In 1983, the Space Telescope Science Institute (STScI) began operations at The Johns Hopkins University in Baltimore, Maryland. The staff of STScI would evaluate proposals for telescope time and manage the resulting telescope observations.

Delays stemming from underestimating the costs and engineering requirements of the state-of-the-art telescope required moving the launch date from December 1983 to the second half of 1986. NASA re-examined interfaces, instruments, and assemblies. The building of the Optical Telescope Assembly encountered engineering challenges. Scientific instruments, such as the Wide Field/Planetary Camera (WF/PC), underwent redesign, removing weight and redundancy.

To maintain and upgrade the space telescope, plans were made to conduct servicing missions in orbit versus returning the telescope to Earth and refurbishing it on the ground. It was an innovative concept that would be even easier on a budget. The project was renamed the Hubble Space Telescope after astronomer Edwin Hubble, who showed that other galaxies existed beyond our own. He also devised a classification scheme that categorized galaxies by shape. By 1985, the telescope was assembled and ready for launch.

However, in 1986, disaster struck. The Challenger accident forced NASA to ground the space shuttle fleet for two years. The Hubble project used that time to perform additional work on the telescope. Solar panels were improved with new solar cell technology. The aft shroud (the end of the telescope that houses the science instruments) was modified to make instrument replacement during servicing easier. Computers and communication systems were upgraded. The space telescope was subjected to further stress tests to prepare for the harsh conditions of liftoff and space.

FOR MORE INFORMATION:
The History of Hubble –
https://science.nasa.gov/mission/hubble/overview/the-history-of-hubble/



The space telescope had several launch delays. These included a long delay due to the 1986 loss of the space shuttle Challenger during launch, after which NASA delayed all flights until better safety improvements and protocols were in place. On April 24, 1990, the space shuttle Discovery lifted off from Earth with the Hubble Space Telescope nestled securely in its bay.

Shortly after Discovery entered its orbit around Earth, the crew opened the shuttle's cargo bay doors. They waited several hours to allow any oxygen from Earth's atmosphere to vent into space. This reduced the chance of electrical arcing in some components when main power was supplied to Hubble from Discovery's flight deck.

Once Hubble had power, the verification team activated the observatory's onboard command computer and checked its memory. They also activated the system that takes automatic control of the telescope, a system called "Safe Mode," to protect the telescope if a major hardware failure occurs.

On the morning of its second day in orbit, April 25, 1990, the Discovery crew switched on Hubble's internal power and deactivated the power supply from the shuttle. The shuttle's robotic CANADARM lifted Hubble out of the cargo bay, suspended it above the crew cabin, with its aperture door pointed away from the Sun.

The verification team almost immediately told Hubble to unfurl its solar arrays so that its six batteries could start recharging. Next, they deployed the telescope's two high-gain antennas and activated its pointing systems. Although some glitches arose, all were worked out.

After each system was tested, the shuttle's robotic arm released its hold on Hubble, allowing it to freely orbit. The shuttle then backed away into a parallel orbit with Hubble. Discovery and Hubble orbited Earth together for about two days, just in case problems occurred that required the astronauts to take corrective action.

After further testing from the control center at Goddard Space Flight Center in Greenbelt, MD, Hubble would be ready to peer into the vast unknown of space, offering a glimpse of the distant cosmos.

IMAGE:
Hubble's launch onboard the space shuttle Discovery on April 24, 1990
Hubble's initial release from the cargo bay on April 25, 1990

FOR MORE INFORMATION:
The History of Hubble –
https://science.nasa.gov/mission/hubble/overview/the-history-of-hubble/
Deployment –
https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/deployment/


THE MISSION
Overview
Design
Servicing
Observations
Illustration of the Andromeda Galaxy and the Milky Way Collision

Hubble in Detail

INTERNATIONAL PARTNERSHIP
NASA, ESA

LAUNCH DATE
April 24, 1990

LAUNCH VEHICLE
Discovery (STS-31)

MASS
27,000 pounds (12,200 kg)
as of Servicing Mission 4

MAXIMUM DIAMETER
14 feet (4.2 m)

LENGTH
43 feet (13 m)

ORBIT HEIGHT
320 miles (515 km)

ORBIT PERIOD
95 minutes to complete one orbit around Earth

ORBIT VELOCITY
About 17,000 miles per hour (27,000 kilometers per hour)

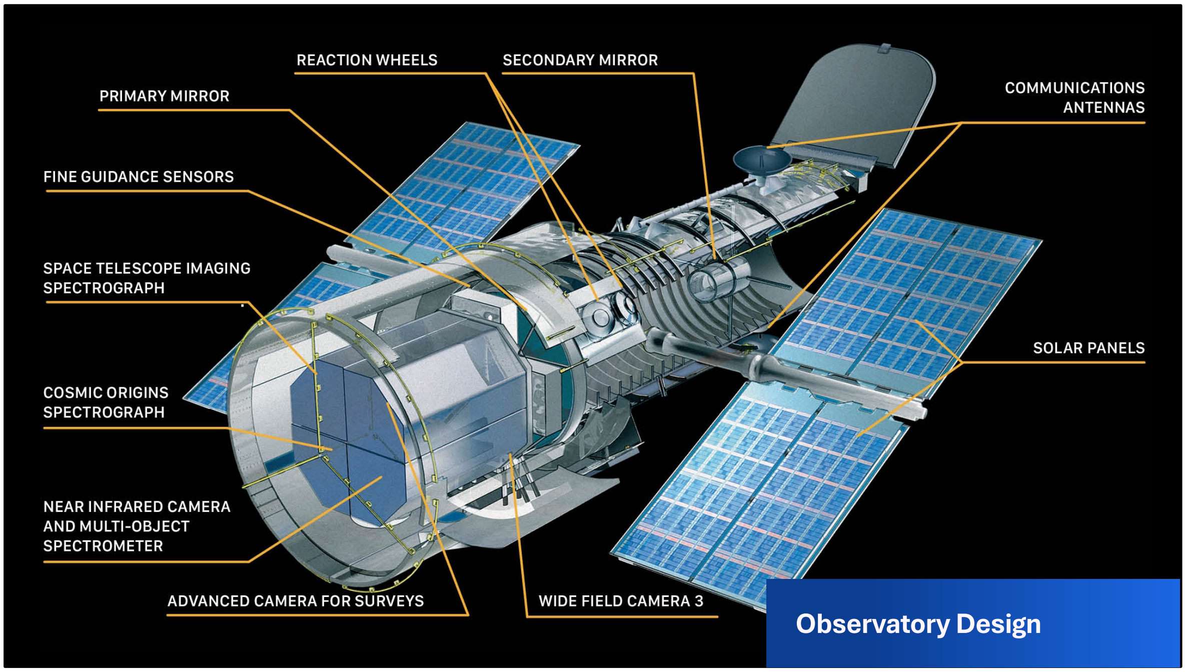
The Hubble Space Telescope is the first astronomical observatory placed into orbit around Earth with the ability to record images in wavelengths of light spanning ultraviolet to near infrared. Launched on April 24,1990 aboard the space shuttle Discovery, Hubble orbits over 300 miles (482 km) above Earth's surface. It completes roughly 15 orbits per day, circling Earth approximately once every 95 minutes. The observatory moves at a speed of about five miles (8 km) per second, fast enough to travel across the United States in about 10 minutes.

While Hubble orbits, its primary mirror collects light from objects near and far. Its nearly 8 foot (2.4 meter) primary mirror is smaller than those of many professional Earth-based observatories. What makes Hubble so powerful is its position above Earth's atmosphere. That location offers Hubble a pristine view of the universe and allows it to see wavelengths that are blocked or partially filtered by the atmosphere. Hubble can resolve objects 1,000 times better than the human eye. That's enough to see two fireflies separated by about 10 feet (3 meters) from roughly the distance between New York City and Tokyo (about 7,000 miles or 11,000 kilometers).

Hubble itself is the size of a school bus. The observatory is 43 feet (13.1 meters) long and 14 feet (4.3 meters) wide at it's base. Hubble weighs about 27,000 pounds (12,247 kilograms) and turns at the speed of a minute hand, taking approximately 14 minutes to go 90 degrees.

IMAGE:
Hubble after release during Servicing Mission 3B in March 2002.

FOR MORE INFORMATION:
About Hubble –
https://science.nasa.gov/mission/hubble/overview/about-hubble/



The observatory is powered by two solar arrays that convert sunlight into electrical energy that is stored in six large batteries. The batteries allow the observatory to operate during the shadowed portions of Hubble's orbit when Earth blocks the satellite's view of the Sun.

In the middle of the spacecraft, near its center of gravity, are four 100-pound (45 kg) reaction wheels used to reorient the observatory. Based upon Sir Isaac Newton's Third Law of Motion – for every action there is an equal and opposite reaction – turning a reaction wheel in one direction causes Hubble to react by turning the opposite way. The satellite knows where and when it should turn based on a target schedule uploaded from the control center. Hubble's main computer then calculates which wheels should slow and which ones spin faster to most efficiently maneuver the spacecraft to the new target.

The observatory uses high-precision gyroscopes (gyros) to detect its rate and direction of motion. The telescope has six gyros, but typical operations only use three of them. Originally, the others served as backups, but gyros eventually wear out and fail. Today, Hubble has three operational gyros, but operates with one. The other two are held in reserve as backups.

In addition to gyros, Hubble has three Fine Guidance Sensors (FGSs) that act within the spacecraft's overall pointing and control system to keep the telescope virtually motionless while observing. Hubble's precision varies by less than 7 milliarcseconds in a 24-hour period when locked on its target. This is equivalent to shining a laser on the head of the president on a dime over 200 miles away for 24 hours.

Commands and data are transmitted between the spacecraft and the control center through two high-gain antennas that communicate through NASA's Tracking Data and Relay Satellite System, which is in geosynchronous orbit. The science data is then forwarded from the control center to the Space Telescope Science Institute in Baltimore, Maryland, via a wide-area network for processing, dissemination, and archiving.

The Hubble Space Telescope has three types of instruments that analyze light from the universe: **cameras, spectrographs, and interferometers**.

Hubble has two primary camera systems to capture images of the cosmos. Called the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3), these two systems work together to provide superb wide-field imaging over a broad range of wavelengths.

Spectrographs practice spectroscopy, the science of breaking light down to its component parts, similar to how a prism splits white light into a rainbow. Any object that absorbs or emits light can be studied with a spectrograph to determine characteristics such as temperature, density, chemical composition and velocity. Hubble currently utilizes several spectrographs including the Cosmic Origins Spectrograph (COS) and the Space Telescope Imaging Spectrograph (STIS). COS and STIS are complementary instruments that provide scientists with detailed spectral data for a variety of celestial objects. While STIS is a versatile, "all purpose" spectrograph that handles bright objects well, COS measures exceedingly faint levels of ultraviolent light emanating from distant cosmic sources, such as quasars in remote galaxies. Wide Field Camera 3 also has spectrographic capability and is often used in the study of exo-planet atmospheres. The Advanced Camera for Surveys and the Near Infrared Camera and Multi-Object Spectrometer (which currently serves as a backup) have their own set of spectrographic capabilities. Working together, these spectrographs provide a full set of spectroscopic tools for astrophysical research.

Hubble's interferometers serve a dual purpose – they help the telescope maintain a steady aim and also serve as a scientific instrument. The three interferometers aboard Hubble are called the Fine Guidance Sensors. The Fine Guidance Sensors measure the relative positions and brightnesses of stars.

FOR MORE INFORMATION:
Observatory Design –
https://science.nasa.gov/mission/hubble/observatory/design/
Instruments –
https://science.nasa.gov/mission/hubble/observatory/design/instruments/
Operating Hubble With Only One Gyroscope –
https://science.nasa.gov/mission/hubble/observatory/design/hubble-one-gyro-mode/

NASA’s Hubble Space Telescope is the first space-based observatory specifically designed for servicing by astronauts while in orbit. The ability to make repairs and upgrade Hubble’s instruments while in orbit became even more important when in 1990, shortly after deployment, NASA discovered that the observatory's primary mirror had an aberration that affected the clarity of the telescope's early images. Astronauts corrected that aberration on their first servicing mission in December 1993. Some 30 years later, Hubble continues to capture our imaginations with its stunning imagery.

Hubble servicing missions involved intensive coordination between NASA's Kennedy Space Center in Florida, Johnson Space Center in Texas, and Goddard Space Flight Center in Maryland. Preparations included astronaut training at all three centers; simulations of shuttle and telescope operations during the mission at Johnson and the Space Telescope Operations Control Center (STOCC) at Goddard; testing and preparing instruments and hardware for flight at Goddard; and preparing launch operations and the space shuttle for launch, flight, and landing at Kennedy.

During the missions, operations took place primarily at Johnson and in Goddard's STOCC. Johnson’s Mission Control Center monitored every aspect of the space shuttle and astronauts, including spacewalks, procedures and schedules, crew activities and health, and in-cabin and cargo bay systems and experiments. The STOCC ground crew handled telescope operations, sending commands to Hubble to place the instruments into "safe hold" (hibernation) or turning them off and on as needed, close the aperture door (which covers the precious optical components), and perform maneuvers to position the telescope for grappling by the shuttle’s robotic arm, operated by astronauts to bring Hubble into the shuttle’s payload bay.

After the repair of existing instruments, installation of new instruments, and replacement of critical hardware or science instruments, STOCC personnel performed tests to make sure each component had power and operated as it should. Many of these tests occurred during the astronauts' sleep cycles, when the STOCC team carried out detailed tests on the newly installed components to determine whether the astronauts needed to perform additional service.

Once the astronauts completed all servicing tasks via a three- to five-day series of spacewalks, the STOCC controllers and Johnson Mission Control prepared the telescope for release. Often this also involved using the shuttle's thrusters to carry Hubble into a slightly higher orbit, a step that prolonged Hubble's life by keeping it from naturally deorbiting due to atmospheric drag.

The astronaut crew used the shuttle's robotic arm to slowly raise Hubble from the payload bay and out into space, where controllers at the STOCC opened Hubble's aperture door and made sure the telescope was functioning normally on its own. Returning Hubble to full science observations after a servicing mission usually took a few months.

IMAGE:
Astronauts Story Musgrave (on the robotic arm) and Jeff Hoffman work to repair and upgrade the telescope during the first servicing mission in December 1993.

FOR MORE INFORMATION:
Missions to Hubble –
https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/

Servicing Mission 1
Dec 2-13, 1993
The first opportunity to conduct planned maintenance on the telescope. Astronauts installed new instruments, including equipment that counteracted the flaw in Hubble's primary mirror.

When Hubble began returning science data to Earth after launch, astronomers did not see the crisp, point-like images of stars they had anticipated. Instead, they saw stars surrounded by large, fuzzy halos of light. They soon realized that the edges of the telescope’s primary mirror had been ground too flat by just a fraction of the width of a human hair, because of a flaw introduced into the test equipment used to evaluate the mirror’s curvature prior to launch. Although perfectly smooth, the mirror could not focus light to a single point. This is known as spherical aberration. This first servicing mission was critical in that it provided hardware and corrective optics that fixed the problem and gave Hubble a sharp, clear view of the universe.

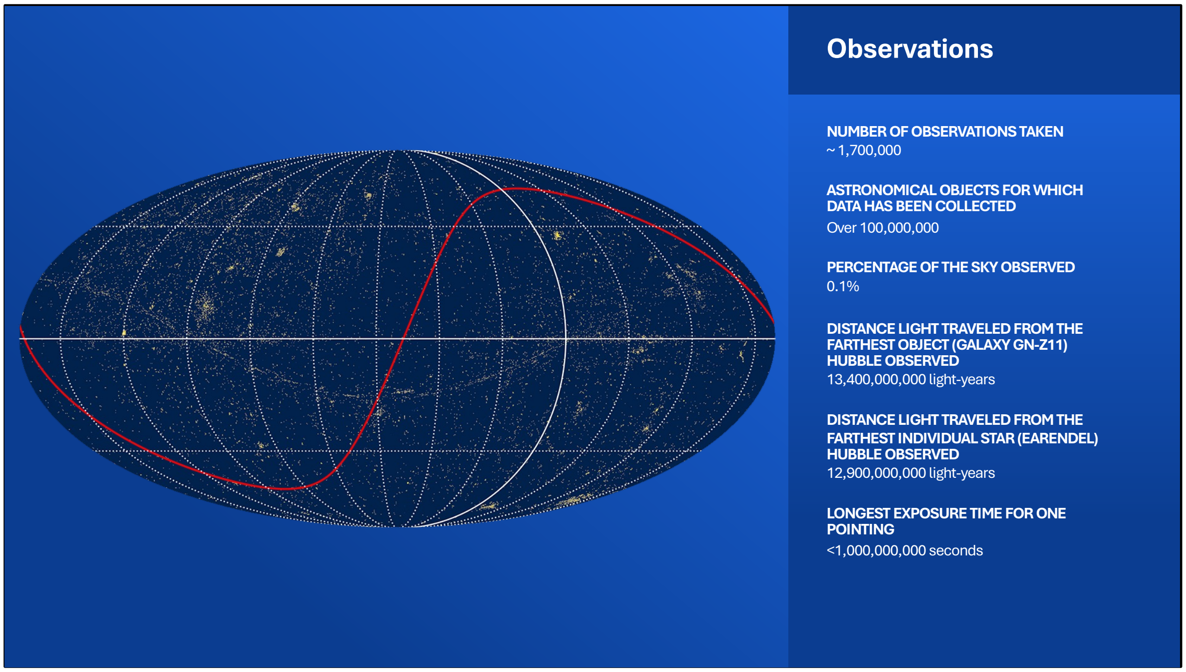
Servicing Mission 2
Feb 11-21, 1997
The second servicing mission extended the range of wavelengths Hubble can see with the installation of two new instruments and increased the observatory's efficiency and performance.

Servicing Mission 3A
Dec 19-27, 1999
What was originally conceived as a mission of preventive maintenance turned more urgent on Nov. 13, 1999, when the fourth of Hubble's six gyros failed. Hubble required at least three of its stabilizing gyros to conduct science at that time. Hubble entered a state of dormancy called safe mode while the telescope awaited repairs. To bring Hubble back into operation more quickly, NASA split the third servicing mission into two parts.

Servicing Mission 3B
Mar 1-12, 2002
During SM3B, astronauts replaced Hubble's solar panels and installed the Advanced Camera for Surveys, which took the place of Hubble's Faint Object Camera, the telescope's last original instrument.

Servicing Mission 4
May 11-24, 2009
The Hubble Space Telescope was reborn with Servicing Mission 4 (SM4). The fifth and final serving mission left the observatory at the peak of its scientific capability and prepared it for many years of further scientific discovery.

FOR MORE INFORMATION:
Servicing Mission 1 –
https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-1/
Servicing Mission 2 –
https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-2/
Servicing Mission 3A –
https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-3a/
Servicing Mission 3B –
https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-3b/
Servicing Mission 4 –
https://science.nasa.gov/mission/hubble/observatory/missions-to-hubble/servicing-mission-4/



Hubble has made more than 1.6 million observations over the course of its lifetime. Over 21,000 peer-reviewed science papers have been published on its discoveries, and those papers have been cited in other papers over 1.2 million times. Those observations have included over 100,000,000 astronomical objects. Every current astronomy textbook includes contributions from Hubble.

Space is a big place. Even though Hubble has taken all those observations on all those objects for over 35 years, it has only looked at one tenth of one percent of the sky.

Number of observations taken - over 1,600,000
Astronomical objects for which data has been collected - 108,000,000
Percentage of the sky observed - 0.1%
Distance light traveled from the farthest object (galaxy GN-z11) observed - 13,400,000,000 light-years
Distance light traveled from the farthest individual star (Earendel) Hubble observed - 12,900,000,000 light-years
Longest exposure time for one pointing (Hubble Ultra Deep Field) - 1,000,000,000 seconds (~11 days)
Number of countries that have won proposals for observing time on Hubble – 39
Astronomers that have written science papers based on Hubble data – 25,000

The following slides represent a small sample of Hubble's thought-provoking discoveries and images. Selecting this set from the thousands of awe-inspiring Hubble observations was difficult, but they serve to highlight some of Hubble's greatest scientific achievements to date.

IMAGE:
A celestial map of Hubble's observations.

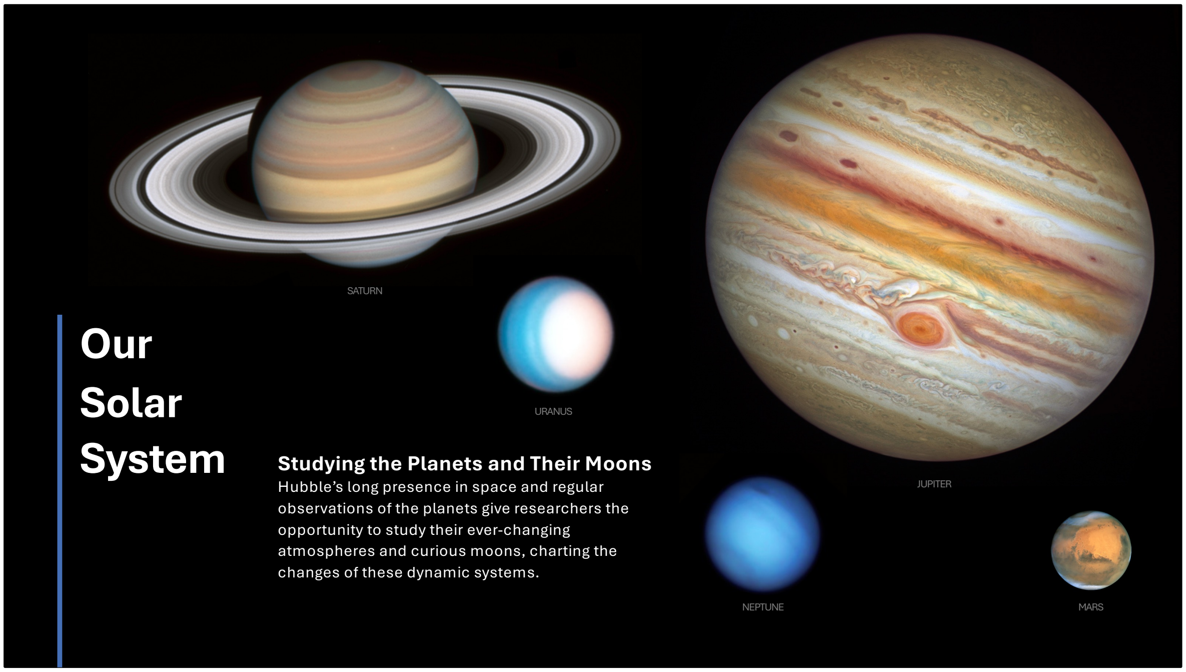
FOR MORE INFORMATION:
Hubble by the Numbers –
https://science.nasa.gov/mission/hubble/overview/hubble-by-the-numbers/
Science Highlights –
https://science.nasa.gov/mission/hubble/science/science-highlights/

Telescopes have a particular range of light that they can detect. Hubble's domain extends from the ultraviolet through the visible (which our eyes see) and into the near-infrared. This range has allowed Hubble to deliver stunning images of stars, galaxies, and other astronomical objects that have inspired people around the world.

The telescope has tracked interstellar objects as they soared through our solar system, watched a comet collide with Jupiter, and discovered moons around Pluto. It has found dusty disks and stellar nurseries throughout the Milky Way that may one day become fully fledged planetary systems and studied the atmospheres of planets that orbit other stars. Hubble has peered back into our universe's distant past, to locations more than 13.4 billion light-years from Earth, capturing galaxies merging, probing the supermassive black holes that lurk in their depths, and helping us better understand the history of the expanding universe.

IMAGE:
The Bubble Nebula (NGC 7635).

FOR MORE INFORMATION:
Science Highlights –
https://science.nasa.gov/mission/hubble/science/science-highlights/
Science Themes –
https://science.nasa.gov/mission/hubble/science/science-themes/



Studying the Planets and Their Moons

Hubble's long presence in space and regular observations of the planets – Jupiter, Saturn, Uranus, Neptune, and Mars – give planetary astronomers the opportunity to study their ever-changing atmospheres and curious moons, charting the changes of these dynamic systems.

In 1994, just four years into its long tenure of collecting data, Hubble watched as 21 fragments of Comet Shoemaker-Levy 9 bombarded the giant planet Jupiter with a sequential train of impacts. Each fragment left a temporary black scar that revealed deeper layers of the planet's atmosphere. It was the first time astronomers witnessed such an event. Hubble observed another impact in 2009, when a suspected asteroid plunged into Jupiter's atmosphere and left a temporary dark feature the size of the Pacific Ocean.

Using Hubble, astronomers tracked Jupiter's Great Red Spot, a giant swirling storm slightly larger than Earth, and found that it is shrinking and jiggling. The spot's outer winds are speeding up while toward its center they are moving significantly more slowly.

Hubble captured brilliant curtains of light, called auroras, on Jupiter, Saturn, and Uranus. Auroras develop when electrically charged particles trapped in a planet's magnetic field spiral inward at high speeds toward the north and south magnetic poles. When these particles hit the upper atmosphere, they excite atoms and molecules there, causing them to glow in a similar process to that of a neon light.

Hubble expanded upon the NASA Voyagers' observations of Neptune and Uranus. It finding that Neptune's southern hemisphere's 'Great Dark Spot' vanished in 1994, then spotted another dark storm in Neptune's northern hemisphere a year later. Hubble's decades of observations revealed that Neptune's storms last for a few years before vanishing or fading away and that this cycle correlates to the Sun's cycle of activity.

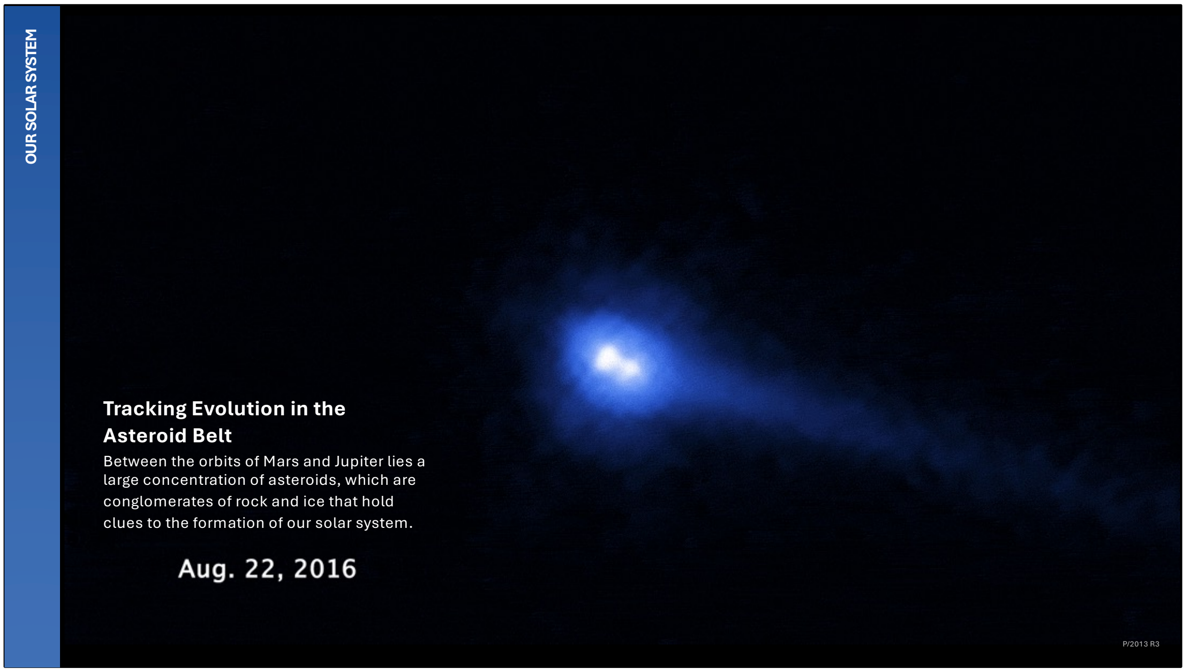
Hubble also helped astronomers calibrate archival Saturn data from four separate missions. The precision of Hubble's Space Telescope Imaging Spectrograph (STIS) and its ability to see ultraviolet light, allowed researchers to compare STIS UV observations of Saturn to 40 years of UV data from the Voyager and Cassini missions, and the International Ultraviolet Explorer. They discovered that icy ring particles raining on Saturn's atmosphere at specific latitudes and seasonal effects cause atmospheric heating. Researchers are testing to see if this unexpected interaction can help define new ways of examining distant exoplanets for extended Saturn-like ring systems.

Hubble found the best evidence yet for an ocean of liquid under an ice crust on Jupiter's moon Ganymede, the largest moon in the solar system. This subsurface ocean may have more water than all of Earth's surface. Hubble also recorded evidence of short-lived changes in the atmosphere above the surface of Jupiter's moon Europa – the result of gas plumes expelled from a subsurface ocean.

In 2003, astronomers using Hubble discovered two small moons around Uranus, called Cupid and Mab. The moons are about 8 to 10 miles across (12-16 km), or roughly the size of San Francisco. Hubble also detected two large outer rings around Uranus.

Ten years later researchers found a small, faint moon called Hippocamp in images Hubble took of Neptune between 2004 and 2009. Astronomers discovered the moon while studying faint ring-arcs around the planet. Then they combed through 150 archived Hubble images of Neptune looking for the moon. Using those Hubble images, they were able to plot Hippocamp's 23-hour orbit around Neptune.

FOR MORE INFORMATION:
Studying the Planets and Moons –
https://science.nasa.gov/mission/hubble/science/science-highlights/studying-the-planets-and-moons/



Tracking Evolution in the Asteroid Belt

Between the orbits of Mars and Jupiter lies a large concentration of asteroids, which are conglomerates of rock and ice that hold clues to the formation of our solar system. This ‘Asteroid Belt’ is the rubble left over from the construction of our solar system, and Hubble’s observations have helped shape our understanding of their interactions and compositions.

Hubble watched the slow disintegration of asteroid P/2013 R3 into 10 smaller pieces. The Hubble data revealed that the fragments are drifting away from each other at a leisurely one mile per hour (1.6 km) – slower than the speed of a strolling human – which suggests the breakup is not the result of a collision.

Astronomers using Hubble witnessed the impact of two asteroids in the asteroid belt. Hubble observations showed a bizarre, X-shaped pattern of filamentary structures near the point-like core of an object with trailing streamers of dust. This complex structure suggested the small body was the product of a head-on collision between two asteroids traveling five times faster than a rifle bullet. The observation helped support the idea that the asteroid belt is slowly eroding through collisions.

In 2013, Hubble observed an asteroid with six comet-like tails of dust radiating from it like spokes on a wheel. Unlike all other known asteroids, which appear simply as tiny points of light, this asteroid resembles a rotating lawn sprinkler. Computer models of the object suggest the tails may have formed through a series of dust-ejection events.

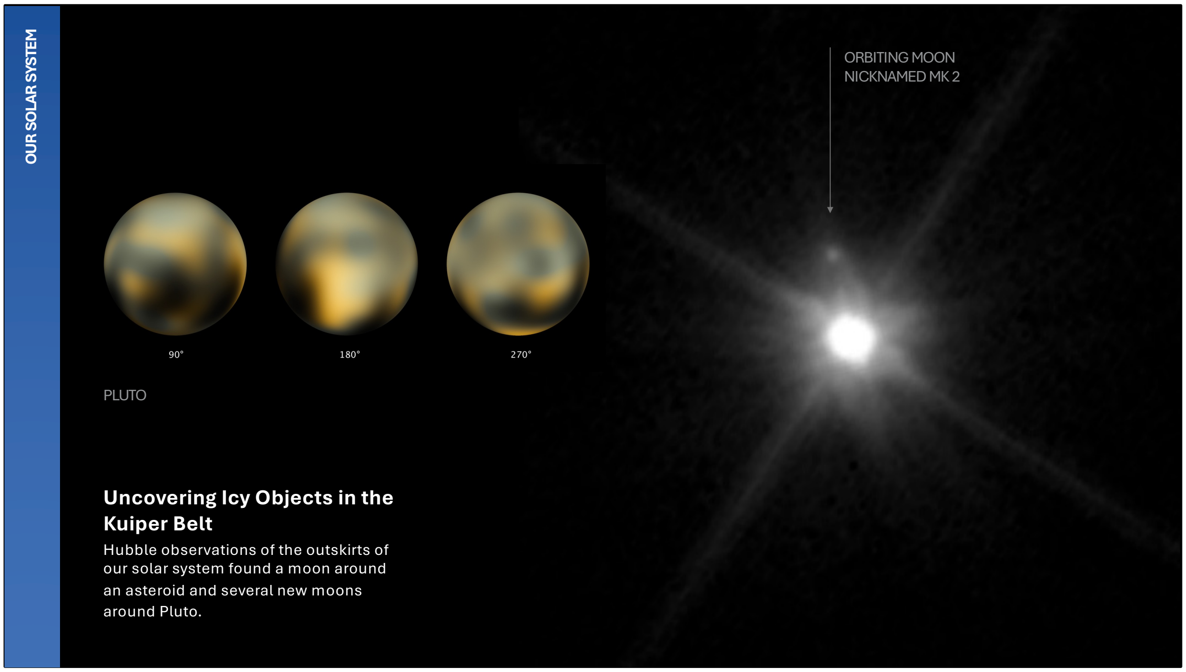
Hubble also observed the first known binary asteroid that also looks like a comet. The asteroid duo orbits each other and has a tail of dust like a comet. The asteroid, called

300163 (2006 VW139), likely broke into two pieces some 5,000 years ago due to its fast rotation.

Hubble captured images of the two most massive objects in the Asteroid Belt, Ceres and Vesta, to help NASA better plan the Dawn spacecraft's visit to these two worlds. Hubble's observations of Ceres revealed bright and dark regions on the asteroid's surface that could be topographic features, such as craters, and/or areas containing different surface material. Large impacts may have caused some of these features and potentially added new material to the landscape.

Hubble images of Vesta allowed researchers to map its southern hemisphere, a region dominated by a giant impact basin formed billions of years ago. Hubble discovered the basin and its central peak through observations made in 1997. The basin's width is 95 percent of Vesta's average diameter and about 12 miles (19 km) deep. Its central peak rises 12-16 miles (19-25 km) and is more than 100 miles (160 km) wide. If Earth had a crater of proportional size, it would fill the Pacific Ocean basin. Hubble's sharp "eye" saw features as small as about 37 miles (60 km) across on Vesta.

FOR MORE INFORMATION:
Tracking Evolution in the Asteroid Belt –
https://science.nasa.gov/mission/hubble/science/science-highlights/tracking-evolution-in-the-asteroid-belt/



Uncovering Icy Objects in the Kuiper Belt

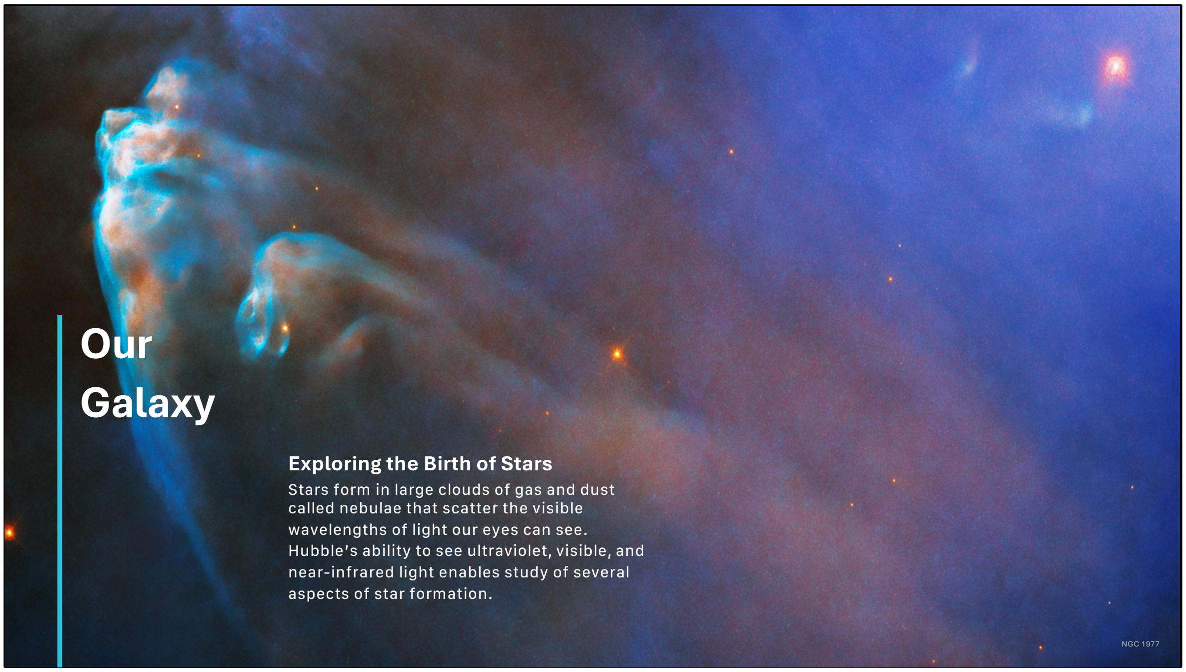
Hubble observations of the outskirts of our solar system found a moon around an asteroid and several new moons around Pluto. These observations played a critical role in helping NASA plan the New Horizons spacecraft's flyby of Pluto and beyond. They allowed the mission's team to refine maps of Pluto's surface in preparation for the rendezvous with Pluto and its moons.

Hubble spied four previously unknown moons orbiting icy Pluto. The tiny moons Nix and Hydra were the first ones Hubble spotted, followed by the even tinier Kerberos and Styx. Astronomers later discovered that Nix and Hydra are rotating chaotically and unpredictably as they orbit the dwarf planet.

Hubble also uncovered two potential Kuiper Belt objects that the New Horizons spacecraft could target on its outward journey past Pluto. On Jan. 1, 2019, New Horizons flew past one of these objects – called Arrokoth – capturing up-close imagery that revealed its double-lobed structure in fine detail, complete with fractures and pitting.

Hubble also discovered a 100-mile-wide (160 km) moon in orbit around Makemake, the second-brightest icy dwarf planet in the Kuiper Belt. Makemake is 4.8 billion miles (7.7 billion km) from the Sun and approximately 870 miles (1,400 km) across. Oddly, the moon is as dark as charcoal, while Makemake is as bright as fresh snow.

FOR MORE INFORMATION:
Uncovering Icy Objects in the Kuiper Belt –
https://science.nasa.gov/mission/hubble/science/science-highlights/uncovering-icy-objects-in-the-kuiper-belt/



Exploring the Birth of Stars

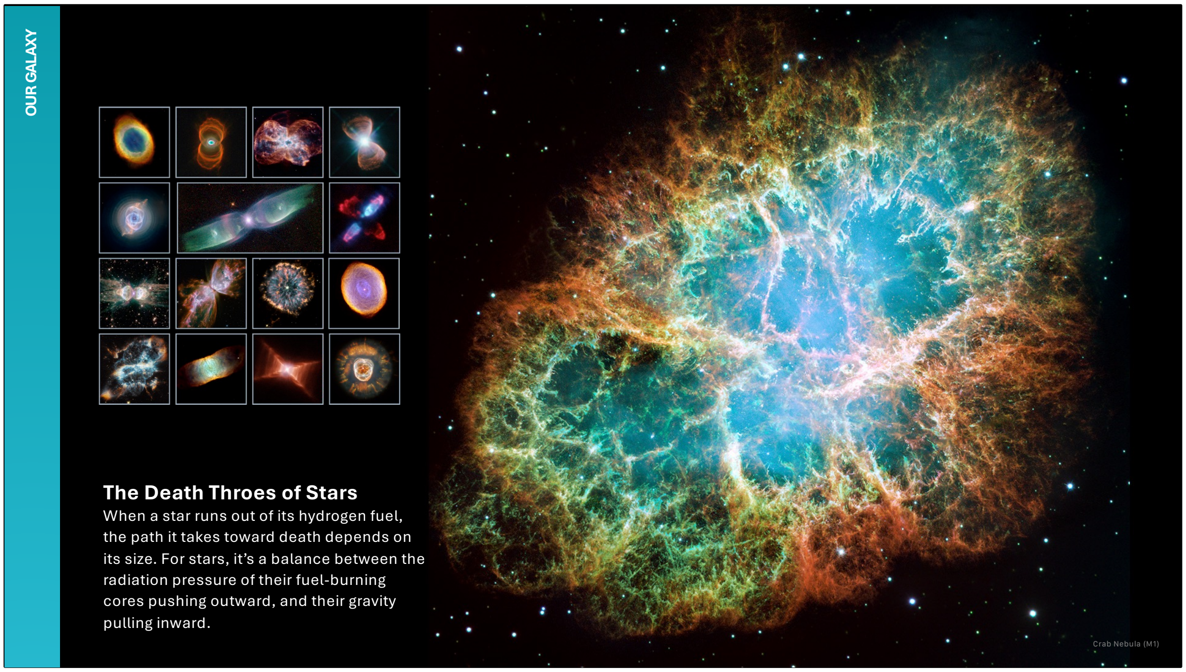
Stars form in large clouds of gas and dust called nebulae that scatter the visible wavelengths of light our eyes can see. Hubble's capability to see ultraviolet, visible, and near-infrared light enables study of several aspects of star formation. Young stars shine brightly in ultraviolet light, while visible light reveals the structure of star-forming clouds, the shock waves induced by jets from forming stars, and colorful ionized gas in the nebulae energized by young stars. Infrared light's longer wavelengths can pass through the cloud relatively undisturbed. Hubble's near-infrared instruments and high resolving power can detect this escaping light, revealing deeply embedded regions within these clouds where newborn stars form. These capabilities make it an important tool in the study of developing stars.

Hubble's observations of nebulae reveal bizarre landscapes sculpted by radiation from young, exceptionally bright stars. The observations reveal the violent process of star birth that produces intense ultraviolet radiation and shock fronts. The radiation clears out cavities in stellar nursery clouds and erodes material from giant gas pillars that are incubators for fledgling stars.

Hubble can capture energetic jets of glowing gas from young stars in unprecedented detail. These jets, called Herbig-Haro objects, are a byproduct of gas swirling into newly forming stars. The jets form when the star's magnetic field channels gas toward the spinning star's poles where it shoots out at supersonic speeds in opposing directions. Hubble's longevity allows astronomers to observe Herbig-Haro objects over time. These observations show us how the jets evolve as they travel through the interstellar medium.

Measuring and studying the motions and changes in shape of Herbig-Haro objects helps astronomers untangle the complicated physical processes that form them, while also providing clues about the environment in which newborn stars develop.

FOR MORE INFORMATION:
Exploring the Birth of Stars –
https://science.nasa.gov/mission/hubble/science/science-highlights/exploring-the-birth-of-stars/

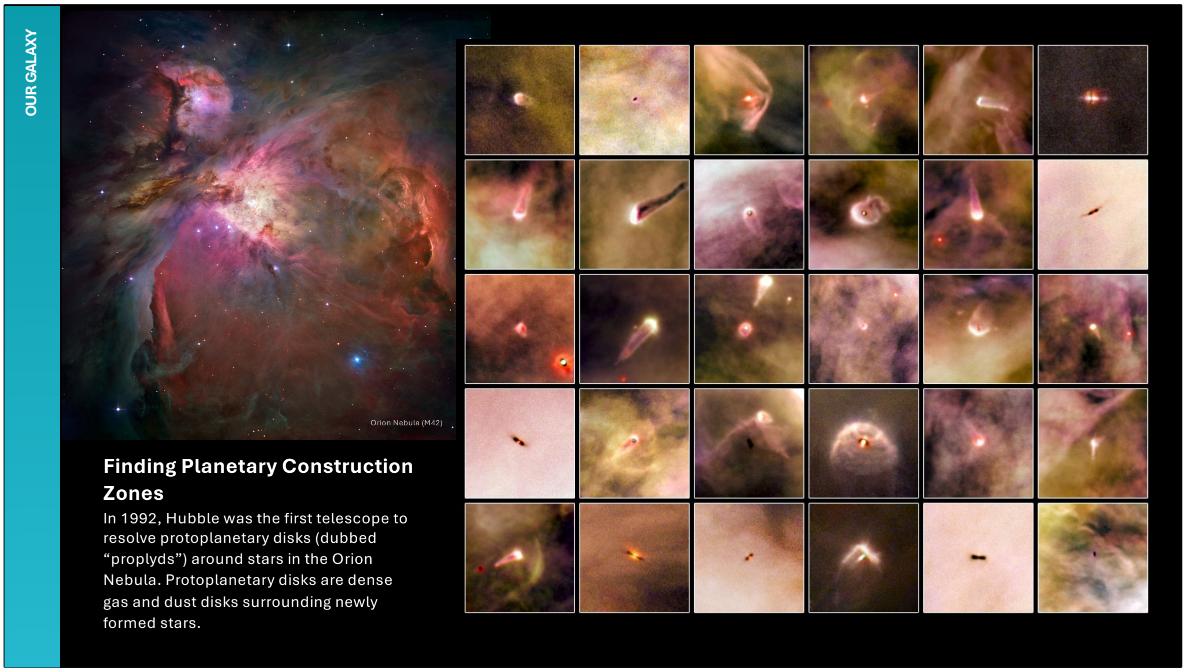


The Death Throes of Stars

When a star runs out of its hydrogen fuel, the path it takes toward death depends on its size. For stars, it's a balance between the radiation pressure of their fuel-burning cores pushing outward, and their gravity pulling inward. When stars run out of fuel, gravity wins this struggle, and the star begins to collapse into black hole, neutron star, or white dwarf depending on its size.

When a medium-sized star begins to die, it sheds its outer layers forming a shell of gas and dust called a "planetary nebula." Before Hubble, ground-based images suggested that planetary nebulae had simple, spherical shapes. Hubble observations revealed unprecedented details that show they are much more varied and complex. These images offer insights into the complex dynamics that accompany a star's release of its outer gaseous layers before it collapses to form a white dwarf or neutron star.

FOR MORE INFORMATION:
The Death Throes of Stars –
https://science.nasa.gov/mission/hubble/science/science-highlights/the-death-throes-of-stars/



Finding Planetary Construction Zones

In 1992, Hubble was the first telescope to resolve protoplanetary disks (dubbed "proplyds") around stars in the Orion Nebula. Protoplanetary disks are dense gas and dust disks surrounding newly formed stars. Hubble's high resolution and sensitivity, along with the Orion Nebula's proximity, have allowed the telescope to image proplyds around nearly 200 stars in the nebula. Proplyds are pancake-like disks of mostly gas and some dust surrounding a young star. They are a prerequisite for the formation of planetary systems.

Hubble also completed the largest and most sensitive visible-light imaging survey of debris disks around stars. Debris disks are belts of dust and rubble that form when objects like asteroids and comets collide. Astronomers use them as "planet detectors." Two particular stars highlight Hubble's observations: TW Hydrae and Beta Pictoris.

Using a mask to block the star's bright light, Hubble scientists spotted a mysterious gap in a vast protoplanetary disk of gas and dust swirling around the star TW Hydrae. The gap is likely the result of a growing, unseen planet gravitationally sweeping up material and carving out a lane in the disk like a snowplow. The 1.9-billion-mile-wide (3 billion km) gap isn't completely cleared of material yet.

More recently, astronomers using Hubble noticed a change in brightness with position in TW Hydrae's disk. Because Hubble has 18 years' worth of observations of the star, the astronomers could assemble a time-lapse movie of the shadow's rotation. They think an unseen planet in the disk is gravitationally pulling on material near the star and warping the inner part of the disk. The twisted, misaligned inner disk is casting its shadow across the surface of the outer disk.

Hubble's longevity also allowed researchers to chart changes in the disk surrounding the 20-million-year-old star Beta Pictoris. In 1998, Hubble's visible-light views of the edge-on disk revealed undulations that computer models suggested were gravitational evidence of budding planets and possibly a companion brown dwarf or bypassing star. Roughly 10 ten years after Hubble's observations, astronomers directly imaged a gas giant planet in the disk, still glowing from its recent formation.

Hubble images trace the disk to within one billion kilometers of the star, a distance that would be the radius of Saturn's orbit about the Sun. Astronomers have uncovered at least two young planets around Beta Pictoris, and Hubble's ground-breaking observations of the disk contributed greatly to those discoveries.

Hubble also captured a vast and complex dust structure extending some 150 billion miles across, enveloping the young, 8-million-year-old star HR 4796A. The bright ring, about 7 billion miles from the star, is a debris field of very fine dust that is likely the result of developing planets colliding near the star. Light pressure from the star, which is 23 times more luminous than the Sun, expelled the dust far into space. The wider debris field is much more extended in one direction than the other. This may be due to the star's motion through space, or it may be the result of a gravitational tug from the star's binary companion, a red dwarf star (HR 4796B) at least 54 billion miles (87 billion km) from HR 4796A.

Hubble was the first observatory to image a forming planet (PDS 70b) in ultraviolet light (UV). Hubble's unique UV capabilities gave planetary scientists the first opportunity to witness extremely hot gas falling onto the planet. The Jupiter-sized world is slowly accumulating matter, allowing researchers to estimate how fast the planet is gaining mass. Located 370 light-years from Earth, the remote planet took about 5 million years to grow to its present size of up to five times the mass of Jupiter. If PDS 70b's accretion rate remains steady for another million years, the planet would only grow by roughly 1/100th of a Jupiter mass.

Hubble's longevity and high resolution also came into play when its Space Telescope Imaging Spectrograph (STIS) and its Near Infrared Camera and Multi-Object Spectrograph (NICMOS) directly imaged a forming Jupiter-like protoplanet, called AB Aurigae b, over a 13-year span. Hubble captured the growing exoplanet embedded in a disk that has distinct spiral structures swirling around the young star AB Aurigae. The planet is about nine times more massive than Jupiter and orbits some 8.6 billion miles from the star – over two times farther than Pluto is from the Sun.

More recently, researchers used the combined power of Hubble and Webb to study the 100-billion-mile-diameter (160 billion km) debris field around the star Vega. They were surprised to find Vega's disk looking smooth with no obvious evidence for large planets plowing through the disk, which is common around other young stars. Hubble sees debris the size of smoke particles, and Webb traces roughly sand-grain-sized particles closer to the star.

FOR MORE INFORMATION:

Finding Planetary Construction Zones –
https://science.nasa.gov/mission/hubble/science/science-highlights/finding-planetary-construction-zones/

Recognizing Worlds Beyond Our Sun

When Hubble launched in 1990, there were no confirmed planets outside of our solar system. Hubble's unique capabilities allow it to explore planetary systems around other stars. Scientists have since established the existence of more than 5,000 extrasolar planets.

Hubble's unique contributions to the planet hunt include taking the first measurements of the atmospheric composition of extrasolar planets. Its observations have identified atmospheres that contain sodium, oxygen, carbon, hydrogen, carbon dioxide, methane, helium, and water vapor. Hubble observations demonstrate that we can detect and measure the basic organic components for life on planets orbiting other stars.

Hubble observed the first known system of seven Earth-sized planets around an ultra-cool dwarf star (TRAPPIST-1) that would allow liquid water to survive on four of the close-orbiting planets. All seven planets orbit closer to their star than Mercury is to our Sun and orbit very close to each other. Hubble observations suggest these planets have more compact atmospheres like those found on Earth, Venus, and Mars.

Astronomers used infrared data from Hubble to make a detailed global map of an exoplanet (WASP-43b) showing the temperatures at different layers in its atmosphere, and the amount and distribution of its water vapor.

In 2004, Hubble began regularly observing what astronomers thought might be an extrasolar planet. They studied the suspected planet for 16 years, tracking its movements around the bright nearby star Fomalhaut. However, something strange was happening as the planet appeared to dim with each successive observation. Then, in 2020, it seemed to vanish completely. Further research revealed that the suspected planet may actually be a vast, expanding cloud of dust produced in a collision between two large bodies orbiting Fomalhaut.

Hubble’s exoplanet observations reveal truly strange worlds, including one that absorbs nearly all the light that reaches it. The planet, WASP-12b, is as dark as fresh asphalt. Another, WASP-121b, is an extremely hot, football-shaped world. Hubble observations also confirmed that three super-puffy planets in the Kepler 51 system have extremely low densities. While these planets appear to be as big and bulky as Jupiter, they are actually 100 times less massive, leading researchers to nickname them ‘cotton candy’ planets.

WASP-121b orbits so close to its host star that it is on the verge of ripping apart. Its upper atmosphere reaches a blazing 4,600 degrees Fahrenheit, causing magnesium and iron gas in the atmosphere to escape into space. Hubble observations of WASP-121b represent the first time astronomers detected elements more massive than hydrogen and helium escaping from a hot Jupiter-like planet. They also suggest the planet has a stratosphere, an atmospheric layer where temperature increases with higher altitudes.

Hubble captured another odd, seething-hot world called WASP-12b located some 1,400 light-years away. This planet is as black as fresh asphalt and is unlike other planets in its class. WASP-12b traps at least 94 percent of the visible starlight falling into its atmosphere, heating it to 4,600 degrees Fahrenheit. The planet is twice the size of any planet in our solar system and orbits so close to its host that it is tidally locked, which means the same side always faces the star. Unlike the day side, the planet’s night side is much cooler, some 2,200 degrees Fahrenheit, allowing water vapor and cloud formation. Hubble observations of the day/night boundary detected evidence of water vapor and possibly clouds and hazes in its atmosphere. WASP-12b is about 2 million miles away from its star and completes an orbit once a day.

Hubble uncovered yet another odd and elusive planet called GJ 3470b. This Neptune-sized world is roughly 3.7 million miles from its star, about one-tenth the distance between Mercury and the Sun. The planet is so close to its host star that its atmosphere is evaporating. The escaping gas forms a giant cloud around the planet that Hubble's Space Telescope Imaging Spectrograph detected. Researchers estimate that the planet has lost as much as 35 percent of its atmosphere over its lifetime.

This isn’t the first shrinking, warm, Neptune-sized planet Hubble observed. A few years earlier, Hubble found that one of the warmest known Neptunes (GJ 436b) is also losing its atmosphere. These evaporating Neptunes may explain the existence of so-called hot super-Earths, which could form from a similar process that strips away the atmosphere of Neptune-sized planets, exposing their rocky cores.

Hubble also detected the gaseous spectral "fingerprints" on a star's light of small comets plunging into the star HD 172555. The gravitational influence of a suspected Jupiter-sized planet, depicted in the foreground, may have catapulted the comets into the star located some 95 light-years from Earth.

FOR MORE INFORMATION:
Recognizing Worlds Beyond Our Sun –
https://science.nasa.gov/mission/hubble/science/science-highlights/recognizing-worlds-beyond-our-sun/

Seeing Light Echoes

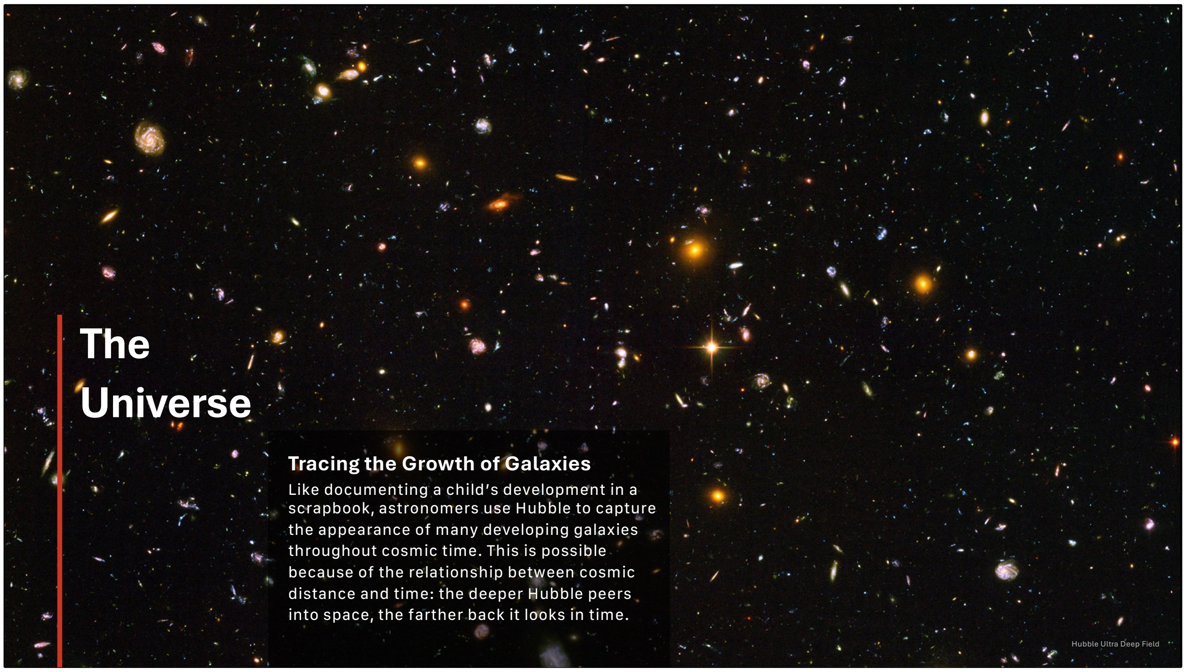
Like ripples on a pond, pulses of light reverberate through cosmic clouds forming echoes of light. Hubble has captured some of the best images of this reverberation of light through space.

In January 2002, an unexplained flash of light from red supergiant star V838 Monocerotis left what looked like an expanding bubble of debris. In fact, the light was simply illuminating clouds that were already in place around the star. Since light travels at a finite speed, the flash took years to reach the most distant clouds and expose them. This phenomenon, called a “light echo,” is reminiscent of sound waves echoing down a canyon and “revealing” its walls.

Two years’ worth of Hubble images revealed “echoing” light in the expanding shell of an exploded star located some 11.4 million light years away in the galaxy M82. An “X” marks the spot where astronomers discovered the supernova, called SN 2014J, on Jan. 21, 2014. The inset images along the top reveal the supernova’s expanding shell of light as it travels through interstellar space, bouncing off a giant dust cloud that extends 300 to 1,600 light-years from the supernova and reflecting back toward Earth.

Hubble captured another light echo around the Cepheid variable star RS Puppis in 2013. Each time the star pulsates, it sends another wave of light into the cloud of gas and dust that surrounds it. These rippling light flashes are similar to the ripples produced in a pond after throwing a series of stones into the water. To our eye, they create a ripple pattern that appears to be expanding outward from the star.

FOR MORE INFORMATION:
Seeing Light Echoes –
https://science.nasa.gov/mission/hubble/science/science-highlights/seeing-light-echoes/



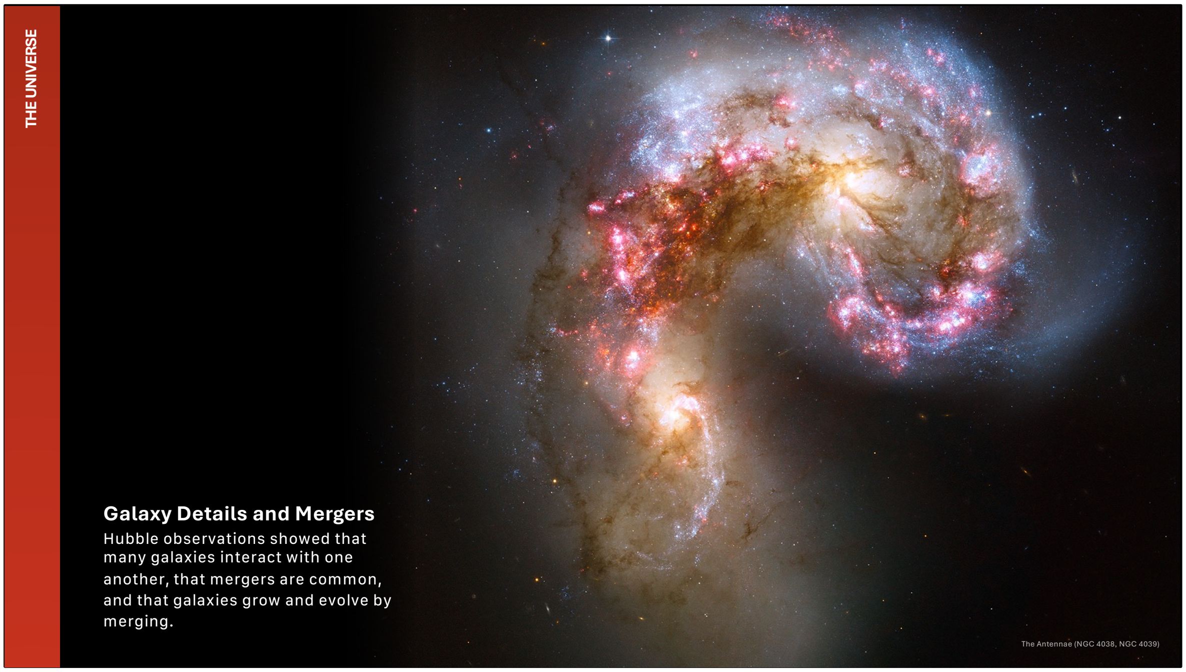
Tracing the Growth of Galaxies

Like documenting a child's development in a scrapbook, astronomers use Hubble to capture the appearance of many developing galaxies throughout cosmic time. This is possible because of the relationship between cosmic distance and time: the deeper Hubble peers into space, the farther back it looks in time. The most distant and earliest galaxies spotted by Hubble are smaller and more irregularly shaped than today's grand spiral and elliptical galaxies. This is evidence that galaxies grew over time through mergers with other galaxies to become the giant systems we see today.

The Hubble Ultra Deep Field contains an estimated 10,000 galaxies. In ground-based images, the patch of sky in which these galaxies reside (roughly the area of sky seen through the eye of a needle held at arm's length) is largely empty. Hubble's deep field view uncovered a menagerie of galaxy types, shapes, sizes, and ages that help us chart how galaxies evolve over time.

Hubble observations of our neighbor, the Andromeda galaxy (M31), show that the galaxy is moving ever closer to an inevitable collision with our own Milky Way. Andromeda is currently 2.5 million light-years away, but it and the Milky Way are moving toward each other under the mutual pull of gravity between the two galaxies and the invisible dark matter that surrounds them both. The merger will begin about 4 billion years from now and will likely result in the creation of a giant elliptical galaxy.

FOR MORE INFORMATION:
Tracing the Growth of Galaxies –
https://science.nasa.gov/mission/hubble/science/science-highlights/tracing-the-growth-of-galaxies/



Galaxy Details and Mergers

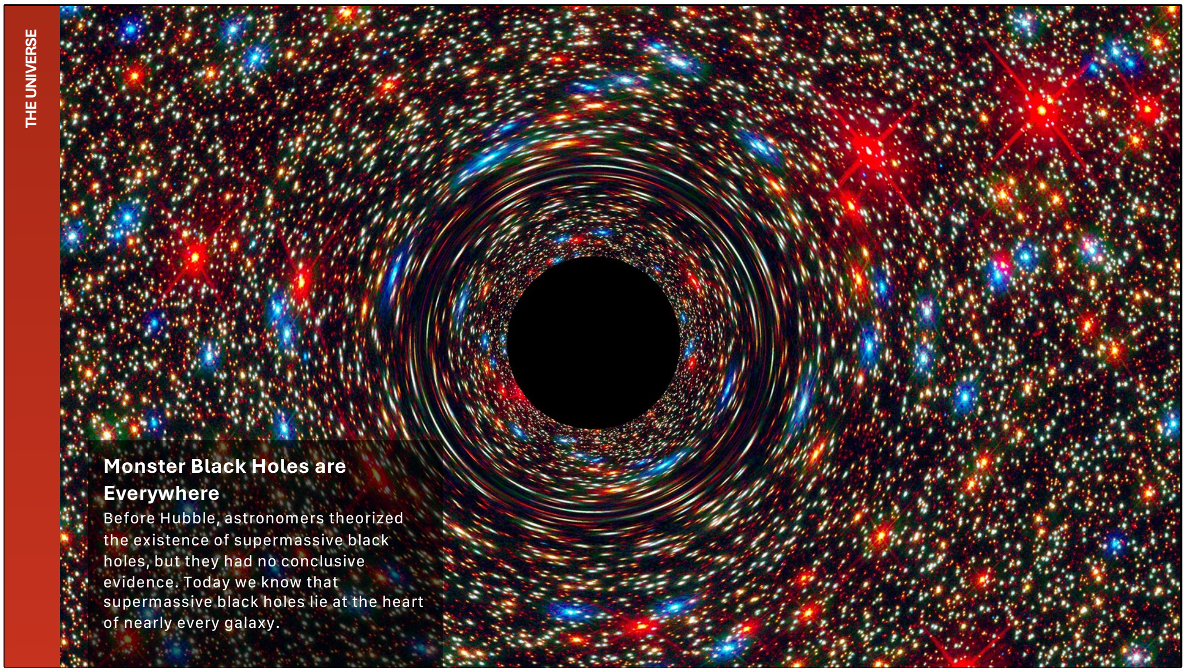
Astronomer Edwin Hubble pioneered the study of galaxies based simply on their appearance and categorized them according to three basic shapes: spiral, elliptical, and irregular. Some 60 years later, the sharp vision of the space telescope named in his honor began seeing unprecedented details in galaxies, revealing intricate, dark dust lanes and glowing knots of star formation. Hubble observations showed that galaxies often interact, that mergers are common, and that galaxies grow and evolve by merging.

The Hubble telescope captured merging galaxies that look like a “Great Pumpkin,” a “Space Triangle,” “Antennae,” and “Mice.” For all their violence, galactic collisions take place at a snail’s pace – over timescales that span several hundred million years. Hubble captures a mere snapshot of these mergers.

Hubble images of the “tadpole-like” Antennae and Mice galaxies reveal the gravitational turbulence these galaxies endure. The interacting duo called Arp 143 (the “Space Triangle”) holds a pair of distorted, star-forming spiral galaxies. Astronomers think the pair passed through each other, igniting a triangular firestorm of new stars.

Mergers like this preview the coming collision between our own Milky Way and the neighboring Andromeda galaxy 4 billion years from now.

FOR MORE INFORMATION:
Galaxy Details and Mergers –
https://science.nasa.gov/mission/hubble/science/science-highlights/galaxy-details-and-mergers/



Monster Black Holes are Everywhere

Before Hubble, astronomers theorized the existence of supermassive black holes, but they had no conclusive evidence. Today we know that supermassive black holes lie at the heart of nearly every galaxy.

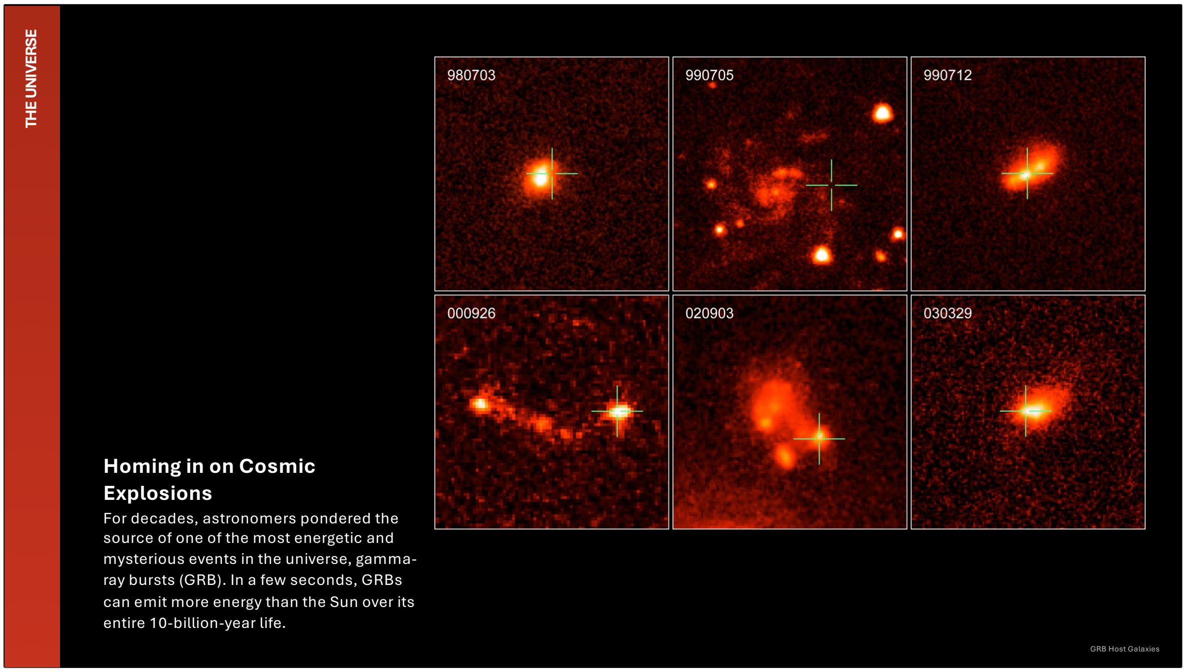
Direct evidence of supermassive black holes didn't come until 1994 when Hubble's Faint Object Camera observed the heart of the giant elliptical galaxy M87. Hubble's observations found a whirlpool of hot, ionized gas orbiting the heart of the galaxy at a speed of about 1.2 million miles per hour (550 kilometers per second). Only a supermassive black hole would have the gravitational power to create a vortex of hot gas at such velocities.

Supermassive black holes are millions to tens of billions of times the mass of the Sun. Hubble images reveal disks of dust that fuel black holes at the centers of galaxies, and a Hubble galaxy census showed that a black hole's mass is dependent on the mass of its host galaxy's central bulge of stars: the larger the galaxy, the larger the black hole. This close relationship may be evidence that black holes grew along with their galaxies, devouring a fraction of the galaxy's mass and intrinsically linking the black hole to the galaxy's evolution.

Black holes aren't all supermassive and lurking at the cores of galaxies. Astronomers estimate that 100 million black holes roam the stars of our Milky Way alone, and these each have a mass closer to that of a single star. In 2022, two teams using Hubble data measured how a suspected isolated black hole's gravity acted like a lens, warping and deflecting the light from a background star. Their measurements indicate the lensing object's size is either a black hole or a compact neutron star.

IMAGE:
This image is from a computer-simulated supermassive black hole at a galaxy's core.

FOR MORE INFORMATION:
Monster Black Holes are Everywhere –
https://science.nasa.gov/mission/hubble/science/science-highlights/monster-black-holes-are-everywhere/



Homing in on Cosmic Explosions

For decades, astronomers pondered the source of one of the most energetic and mysterious events in the universe, gamma-ray bursts (GRB). In a few seconds, GRBs can emit more energy than the Sun over its entire 10-billion-year life. It wasn't until Hubble began observing the visible source of these events that astronomers began to better understand their origins.

In 1997, astronomers employed Hubble's high resolution and sensitivity to hunt down a rapidly dimming fireball in the region of space that had produced a GRB. The explosive remnant rapidly faded, and ground-based observatories could no longer see it. Hubble observations allowed astronomers to continue following the fading source, and clearly showed that it had two components: a point-like object and an extended feature.

Soon after the GRB 990123 observations, Hubble's Wide Field and Planetary Camera 2 captured the first visible light image that associates a gamma-ray burst source with a potential host galaxy. The bright source was not near the center of the galaxy – which might have suggested it came from a black hole at the galaxy's heart – but on the outskirts.

On June 13, 2013, Hubble observed a rapidly fading fireball produced in the aftermath of GRB 130603B, whose initial blast lasted only one-tenth of a second. The Hubble observation revealed a new kind of stellar blast called a kilonova, an explosion that astronomers predicted would accompany short-duration GRBs. This kilonova provided strong evidence that short-duration gamma-ray bursts are the result of a merger of two small, super-dense stellar objects, such as a pair of neutron stars or a neutron star and a black hole.

Then, in August 2017, Hubble was part of a team of observatories that detected the first combined gravitational wave and gamma radiation signal from a binary neutron star merger. Seventy observatories around the globe observed the merger's aftermath. Hubble's precise measurements allowed astronomers to pinpoint the explosion site and revealed the speed of a jet moving at least 99.97% the speed of light.

Today, thanks in large part to Hubble observations, astronomers categorize GRBs into two types: Long GRBs (where the initial burst lasts two seconds or longer) and Short GRBs (where the burst lasts less than two seconds). Short bursts are associated with the collision of either two neutron stars or a neutron star and a black hole. Long bursts stem from the explosive, supernova deaths of massive stars.

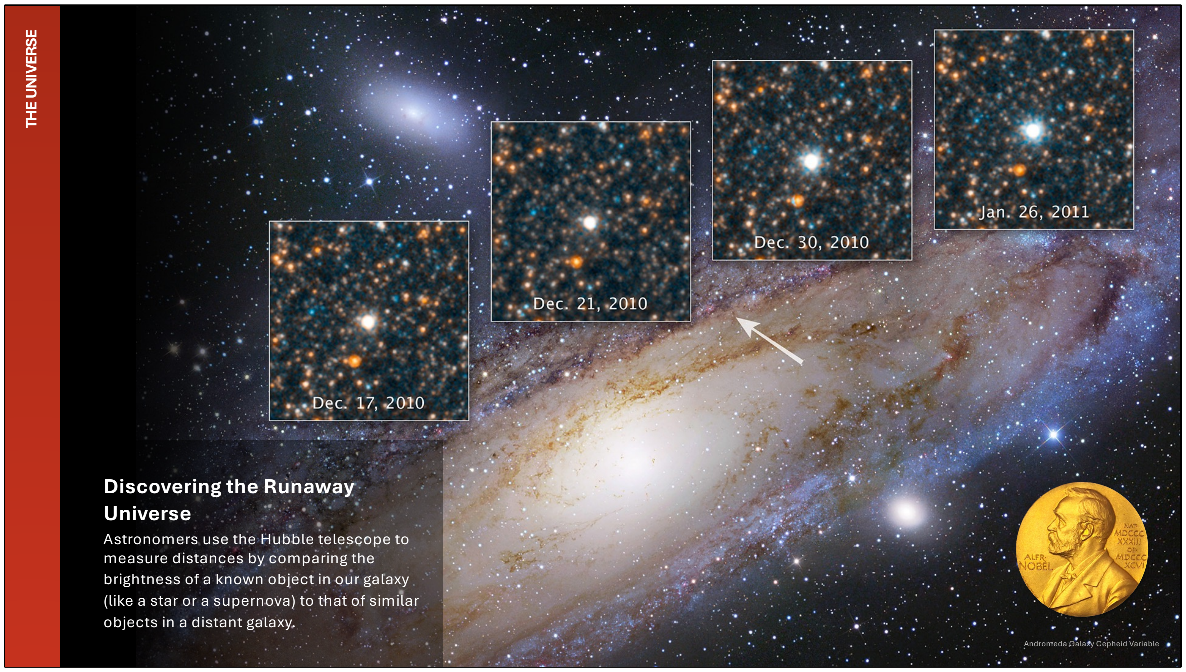
Hubble's observations of supernovae have also played a key role in our understanding of these explosive star deaths. Its first observations of a supernova came just 4 months after its launch, when Hubble's Faint Object Camera resolved an elliptical ring of material around the remnants of Supernova 1987A (SN1987A).

SN 1987A was the brightest exploding star astronomers saw in 400 years. Hubble's sensitivity, resolution, and longevity allow it to keep track of SN1987a's evolution, collecting 7,000 data sets for some 250 scientific proposals as of July 2024. This data revealed rings in different planes in 1994. The bright central ring is about one light-year across and existed when the star exploded. The star likely shed the ring thousands of years before it went supernova. Ultraviolet radiation from the exploding star caused it to glow in early Hubble images. As the gas cooled, the ring faded until the blast's shock wave reached the ring, causing it to brighten again.

Astronomers found evidence of a hypothesized electron-capture supernova by comparing a Hubble image of the supernova, called SN 2018zd, with earlier Hubble images of the same area of sky. This allowed them to identify the supernova's progenitor star in the galaxy NGC 2146. Stars between eight and 10 times the mass of the Sun theoretically should explode in a different way. Their immense internal pressure would force electrons to fuse with atomic nuclei, causing a sudden drop in electron pressure that triggers the collapse and subsequent explosion of the star's surrounding layers.

In April 2020, astronomers discovered a supernova inside the interacting Butterfly galaxies (NGC 4568). They quickly trained Hubble on the aftermath and got a ringside view of the supernova in the very earliest stage of exploding. Hubble viewed a region very close to the supernova; examining material ejected by the star in the last year of its life. These observations may provide astronomers with an early warning system for other stars on the brink of an explosive death.

FOR MORE INFORMATION:
Homing in on Cosmic Explosions –
https://science.nasa.gov/mission/hubble/science/science-highlights/homing-in-on-cosmic-explosions/



Discovering the Runaway Universe

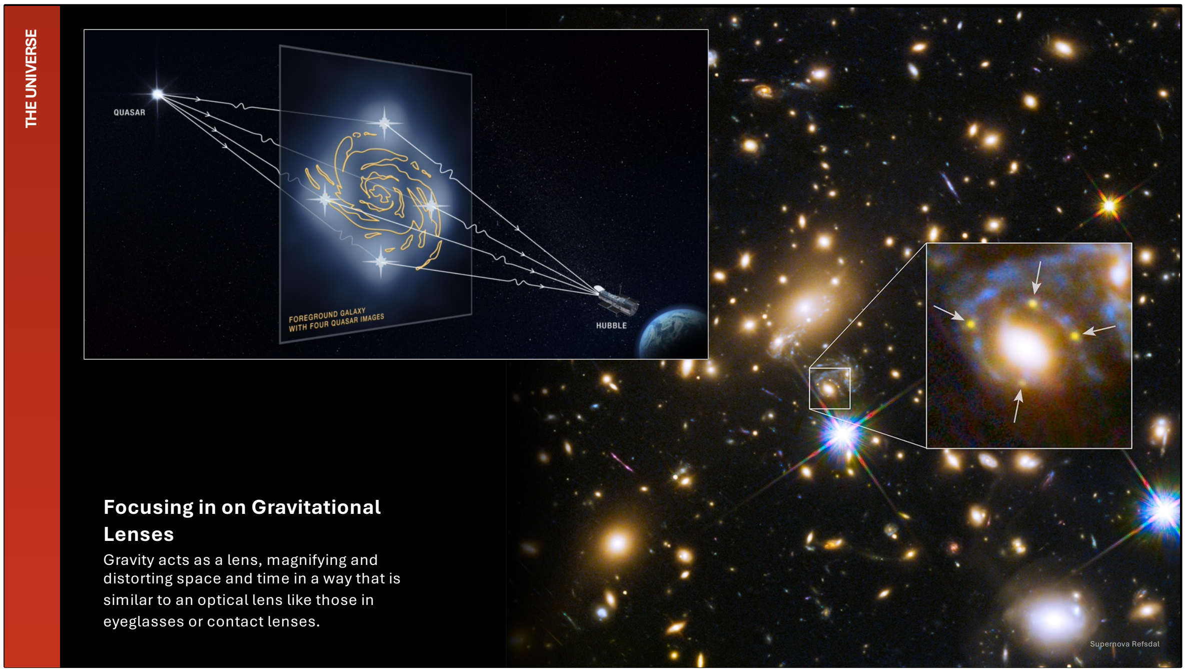
Nearly a century after astronomer Edwin Hubble discovered that the universe is expanding, the telescope named in his honor refined his distance measurements. Astronomers use the Hubble telescope to measure distances by comparing the brightness of a known object in our galaxy (like a star or a supernova) to that of similar objects in a distant galaxy. They then couple those distances with the best galaxy-velocity measurements obtained from other telescopes. After more than three decades of observations, teams using Hubble's extraordinary capabilities have measured the expansion rate to a precision of just over 1%, about eight times more precise than they originally anticipated! This value for the Hubble Constant puts the age of the universe at about 13.8 billion years old. However, there is a twist… Our universe is not only growing, but that expansion rate is accelerating.

In 2011, Hubble observations, along with those of ground-based observatories, surprised astronomers by revealing that the universe is not just expanding but accelerating – a discovery that won the 2011 Nobel Prize in Physics. The difference between the expected expansion rate, which is based on the universe's initial conditions and our present understanding of the universe's evolution, and the measured expansion rate is a puzzle scientists call 'Hubble Tension'.

In 2023, to try to eliminate the possibility of measurement errors, researchers used NASA's James Webb Space Telescope to test their Hubble results. Those observations confirmed Hubble's results, leading some scientists to suggest that something else – not measurement errors – is influencing the expansion rate.

Many scientists believe an invisible force, called "dark energy," causes this acceleration. We can think of dark energy as an "antigravity" or repelling force that pushes galaxies apart by stretching space at an increasing pace. Although current technology does not allow us to directly measure dark energy, we can characterize it by observing its effect on normal matter in the visible universe. From these observations, scientists estimate that dark energy is about 68%, dark matter is about 27%, and normal matter and energy are only about 5% of the entire universe. By studying how dark energy behaves over time, astronomers hope to gain a better understanding of what it is and how it might affect the future of the cosmos.

FOR MORE INFORMATION:
Discovering the Runaway Universe –
https://science.nasa.gov/mission/hubble/science/science-highlights/discovering-a-runaway-universe/



Focusing in on Gravitational Lenses

Gravity acts as a lens, magnifying and distorting space and time in a way that is similar to an optical lens, like those in eyeglasses or contact lenses. As light passes through a gravitational lens, it may take different paths, producing multiple images of the same object. When that light emerges from the lens, we see several contorted images of a single object. Gravitational lenses help boost our view, allowing Hubble to capture faint, distant objects.

Five months after its April 1990 launch, Hubble captured four gravitationally lensed images of a quasar called G2237+0305. Called an Einstein Cross, the image reveals a distant quasar gravitationally lensed four times by a relatively nearby galaxy.

The enormous galaxy cluster, MACS J1149.6+2223, located more than 5 billion light-years away, creates a gravitational lens that facilitated two of Hubble's most exciting discoveries using gravitational lenses. The first was Supernova Refsdal. Hubble captured the supernova because the gravitational lens created by a massive galaxy embedded in MACS J1149.6+2223 bent and magnified its light. Refsdal is some 4.3 billion light-years farther than MACS J1149.6+2223 or 9.3 billion light-years from Earth.

First discovered in 2014, astronomers calculated how Refsdal's light might move through MACS J1149.6+2223's enormous gravitational lens and predicted its reappearance. While looking for and finding the supernova's reappearance in MACS J1149.6+2223, they also found an enormous, distant, blue star they nicknamed Icarus.

Icarus is so far away that its light took 9 billion years to reach Earth. Because the star's light had such a long distance to travel, Hubble's observations captured the star as it appeared when the universe was about 30 percent of its current age.

Just four years after the discovery of Icarus, Hubble broke its own record by finding a more distant star, called Earendel, in a gravitational lens created by a huge galaxy cluster called WHL0137-08. The star sits in a ripple of spacetime that produces extreme magnification, allowing Earendel to stand out against its host galaxy, which appears as a red arc. It took Earendel's light 12.9 billion years to reach Earth traveling at 186,000 miles per second (300,000 km per second). Hubble's image captured the star as it appeared when the universe was only seven percent of its current age – within the first billion years after the universe's birth in the big bang – making it the most distant individual star ever seen.

FOR MORE INFORMATION:
Focusing in on Gravitational Lenses –
https://science.nasa.gov/mission/hubble/science/science-highlights/focusing-in-on-gravitational-lenses/

Shining a Light on Dark Matter

More than 80% of the universe is stuff we have never seen. Its gravity drives normal matter (gas and dust) to collect and build up into stars, galaxies, and massive galaxy clusters. Visible matter reveals itself by shining brightly, but astronomers detect dark matter by its gravitational influence on the light we see. By looking at the area around massive galaxy clusters, astronomers can identify warped background galaxies gravitationally lensed by the cluster and reverse-engineer their distortions. Mathematical models of these results shed light on the location and properties of the densest concentrations of matter in the cluster, both visible (normal matter) and invisible (dark matter, indicated by the bluish-purple glow).

FOR MORE INFORMATION:
Shining a Light on Dark Matter –
https://science.nasa.gov/mission/hubble/science/science-highlights/shining-a-light-on-dark-matter/

Mapping the Cosmic Web

Astronomers theorize that the early universe was very smooth, and that the distribution of matter was uniform with tiny variations in density that grew into a web-like pattern. These areas of slightly higher density also had slightly more gravity to attract more matter. Over time, the universe evolved into a web of filaments and vast sheets, largely made of dark matter, which shape the structure of the universe today.

This cosmic web forms the large-scale backbone of the universe. Hubble’s high resolution can make detailed observations that spot minute distortions in how light from distant objects bends around a foreground galaxy cluster. Such observations allowed astronomers to make the first map of a filament funneling matter into the massive galaxy cluster MACS J0717. The astronomers expanded Hubble’s two-dimensional observations by using data from other observatories that measured distances to the galaxies in the filament.

Hubble observations of MACS J0717 and its filament also revealed the first documented collision of four separate galaxy clusters. The collisions are the result of the 13-million-light-year-long filament of normal and dark matter streaming into a region already full of matter.

This composite image of visible light data from Hubble and x-ray data from NASA’s Chandra X-ray Observatory reveals the hot gas (blue) and cooler gas (reddish-purple). Astronomers can estimate the speed and direction of each cluster's motion —

perpendicular to the line of sight — by studying the difference between the average position of the galaxies and the peak in the hot gas. As the filament funnels matter into the cluster, collisions between the gas in two or more clusters causes the hot gas to slow down, dissipating some of its kinetic energy as heat. But the massive and compact galaxies do not slow down as much as the gas does, so they move ahead of it. This allows the researchers to three-dimensionally map the geometry and motion in the system, thereby mapping the large-scale structure of the region located some 5.4 billion light-years from Earth.

Nearly 1,000 hours of Hubble observations similarly enabled an international team of 70 astronomers to create the first three-dimensional map of the web-like, large-scale distribution of dark matter. The map is comprised of 575 slightly overlapping Hubble images that stretch halfway back in time to the beginning of the universe. They reveal a loose network of dark matter filaments, gradually collapsing and growing clumpier over time under the relentless pull of gravity, confirming theories of how structure formed in our evolving universe.

Each slice reveals the changing distribution of dark matter in a discrete epoch of time. Astronomers calibrated each epoch by measuring the cosmological redshift of the lensing galaxies used to map the dark matter's distribution, placing them into different time/distance "slices."

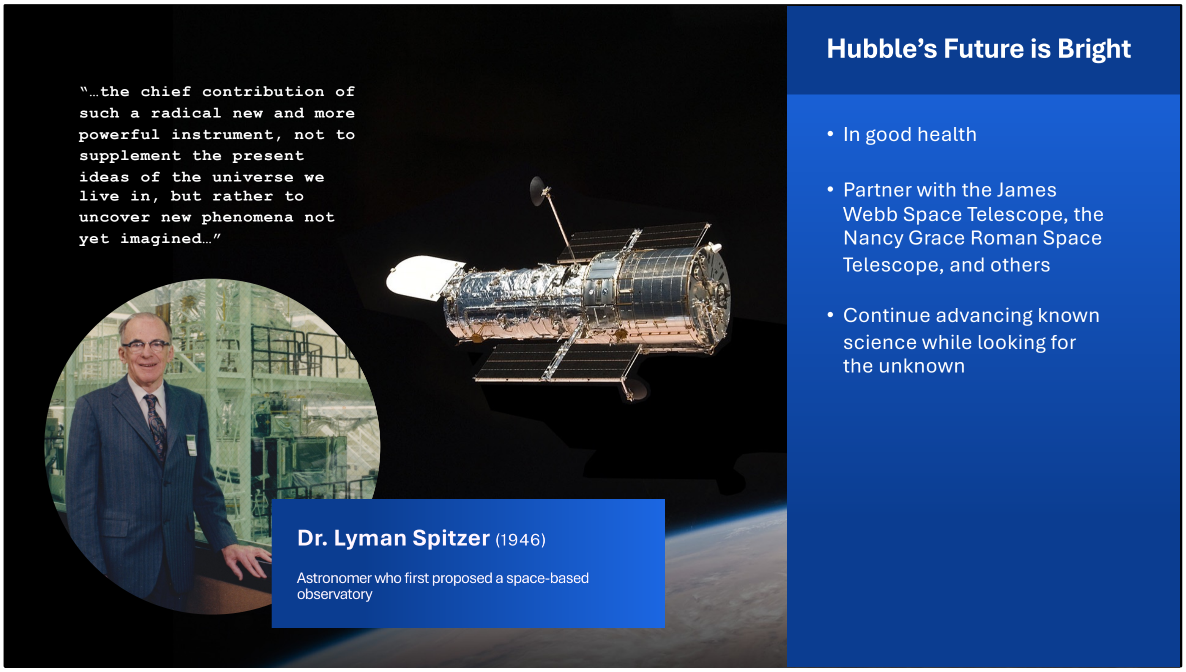
Astronomers combined the slices to create the three-dimensional map of dark matter over time. The three axes of the box correspond to sky position (right ascension and declination), and distance from Earth increasing from left to right (as measured by cosmological redshift). Note how the dark matter clumping becomes more pronounced, moving right to left across the map, from the early universe to the more recent universe, confirming theories of how the large-scale structure of the universe formed and evolved.

Recently, simple single-cell organisms that feed on dead plant material became the analogous counterpart to how the large-scale structure of the universe formed. Researchers developed an algorithm that mimics the brainless slime mold's efficiency at building complex filaments to capture new food. They then applied the algorithm to data containing the locations of 37,000 galaxies mapped by the Sloan Digital Sky Survey. The galaxies are analogous to the slime mold's food. The algorithm revealed the striking similarity between how the slime mold builds complex filaments to capture new food, and how gravity constructs the cosmic web filaments between galaxies and galaxy clusters.

After the three-dimensional computer model estimated the location of the cosmic filaments, the astronomers used archival Hubble observations to detect and study the gas permeating the web at points along those predicted filaments. They examined the ultraviolet light from 350 distant quasars in the Hubble Spectroscopic Legacy Archive. Because these quasars are so far from the galaxies, the researchers were able to use the Hubble data to look for the telltale absorption of undetected hydrogen gas in the spectroscopic signature of the quasars and link the gas to the universe's large-scale structure.

FOR MORE INFORMATION:

Mapping the Cosmic Web –
https://science.nasa.gov/mission/hubble/science/science-highlights/mapping-the-cosmic-web/



Hubble's health is good. Redundancies exist in all critical systems except a few. In those cases, alternate operational scenarios have been developed to work around a possible failure, allowing Hubble to continue to produce ground-breaking science. The Hubble team anticipates continuing to do exciting, extraordinary, and prize-winning science into the next decade.

Hubble is one in a fleet of telescopes across the globe and in space that study the universe, and it often collaborates with these other observatories to make discoveries. Those collaborations take many forms, from formal agreements to community-wide observations of an event.

Hubble observation time is generally proposed and won through the standard Hubble cyclical call for proposals. Proposals can request observing time on the James Webb Space Telescope, Chandra X-ray Observatory, the Transiting Exoplanet Survey Satellite (TESS), NOIRLab (formerly National Optical-Infrared Astronomy Research Laboratory) telescopes, National Radio Astronomy Observatory (NRAO) facilities, and the European Space Agency's XMM-Newton, in conjunction with requests for Hubble observations. Future observatories will also partner with Hubble as they come online. The next is NASA's highly-anticipated Nancy Grace Roman Telescope.

NASA's program to explore the solar system includes spacecraft that have studied the inner and outer solar system and have traveled well beyond the realm of the Sun's influence. Unlike Hubble, these probes leave Earth's orbit and travel to the solar system object of interest. At times, it is advantageous to use Hubble to help find targets for these probes or do collaborative observations of a specific event. These include the past (New Horizons that visited Pluto), the present (Juno that is at Jupiter), and the future (LUCY that is on its way to study the composition of Trojan asteroids in Jupiter's orbit).

Many additional missions have partnered with Hubble on science data and mission planning. The lesson is that a team of observatories is often better than one.

Hubble will continue to do exciting, extraordinary, and prize-winning science. The Hubble team anticipates that this success will continue into the next decade.

As Lyman Spitzer dreamed in the 1940's, Hubble is still poised to continue to "uncover new phenomena not yet imagined."

IMAGE:
Lyman Spitzer standing at a cleanroom window with the observatory in the background.

FOR MORE INFORMATION:
Partners in Science –
https://science.nasa.gov/mission/hubble/science/hubbles-partners-in-science/

For more information on Hubble and to enjoy the numerous interactive web apps, videos, images, e-books, and more, visit us at https://nasa.gov/hubble

To stay up to date with Hubble's latest discoveries, products, and information by following @NASAHubble on Facebook, X, and Instagram.

Watch our videos on YouTube and view our science, historical, servicing mission, control center, and other related photos on Flickr.

IMAGE:
Hubble orbiting Earth. An STS-125 crew member aboard the space shuttle Atlantis captured the image as the two spacecraft continued their relative separation on May 19, 2009.

FOR MORE INFORMATION:
YouTube (Hubble Playlist) –
https://www.youtube.com/playlist?list=PL3E861DC9F9A8F2E9

Flickr –
https://www.flickr.com/photos/nasahubble/