RocketSTEM

Vol. 3 • No. 2 • April 2015 • Issue 11

25 years of Hubble

"Equipped with his five senses, man explores the universe around him and calls the adventure Science."

– Edwin Hubble

Welcome to this special supersize issue of Rocket**STEM**. We are devoting the entire issue to celebrating 25 years of discovery by the Hubble Space Telescope.

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Special Thanks

ESA/Hubble • Space Telescope Science Institute • NASA

RocketSTEM • April 2015 • Vol. 3 No. 2 Issue 11 (ISSN: 2326-0661)

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On the Cover: *Bright blue newly formed stars are blowing a cavity in the centre of a fascinating star-forming region known as N90. Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA) - ESA/Hubble Collaboration*

Preceeding Page: *The Hubble Space Telescope, backdropped over Madagascar, is berthed in Endeavour's cargo bay following its capture by the STS-61 astronauts. Credit: NASA*

Celestial fireworks mark Hubble's 25th

The brilliant tapestry of young stars flaring to life resemble a glittering fireworks display in the 25th anniversary Hubble Space Telescope image, released to commemorate a quarter century of exploring the solar system and beyond.

"Hubble has completely transformed our view of the universe, revealing the true beauty and richness of the cosmos" said John Grunsfeld, astronaut and associate administrator of NASA's Science Mission Directorate. "This vista of starry fireworks and glowing gas is a fitting image for our celebration of 25 years of amazing Hubble science."

The sparkling centerpiece of Hubble's anniversary fireworks is a giant cluster of about 3,000 stars called Westerlund 2, named for Swedish astronomer Bengt Westerlund who discovered the grouping in the 1960s. The cluster resides in a raucous stellar breeding ground known as Gum 29, located 20,000 light-years away from Earth in the constellation Carina.

To capture this image, Hubble's near-infrared Wide Field Camera 3 pierced through the dusty veil shrouding the stellar nursery, giving astronomers a clear view of the nebula and the dense concentration of stars in the central cluster. The cluster measures between 6 and 13 light-years across.

The giant star cluster is about 2 million years old and contains some of our galaxy's hottest, brightest and most massive stars.

The nebula reveals a fantasy landscape of pillars, ridges and valleys. The pillars, composed of dense gas and thought to be incubators for new stars, are a few light-years tall and point to the central star cluster. Other dense regions surround the pillars, including reddish-brown filaments of gas and dust.

The brilliant stars sculpt the gaseous terrain of the nebula and help create a successive generation of baby stars. When the stellar winds hit dense walls of gas, the shockwaves may spark a new torrent of star birth along the wall of the cavity. The red dots scattered throughout the landscape are a rich population of newly-forming stars still wrapped in their gas-and-dust cocoons.

Because the cluster is very young – in astronomical terms – it has not had time to disperse its stars deep into interstellar space, providing astronomers with an opportunity to gather information on how the cluster formed.

Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), A. Nota (ESA/STScI), and the Westerlund 2 Science Team.

Hubble Space Telescope:

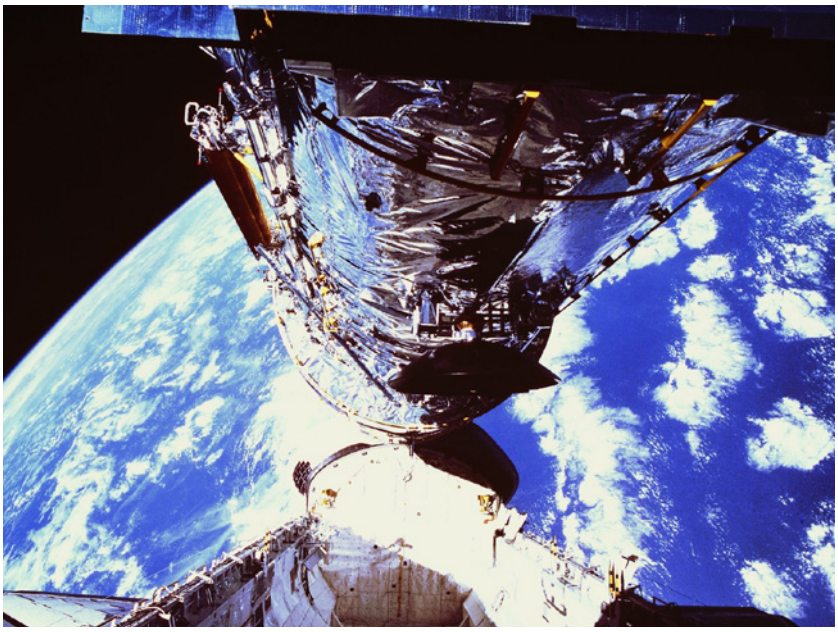
Showing humanity the Universe

By Amy Thompson

Since launching in 1990, the Hubble Space Telescope (HST) has awed and inspired the public with a dazzling array of images. More than just pretty pictures, Hubble has collected 25 years of data, providing unprecedented views and insights into the universe. By observing objects from neighboring planets to the most distant galaxies, Hubble has captured breath-taking photos of supernovae, stellar nurseries, planetary nebulae and more. Follow along as we explore the history of the telescope, its discoveries, and highlight the orbiting observatory's Top 100 images.

Throughout history humans have been turning their heads towards the skies, in an attempt to learn more about the universe. In 1610, Galileo revolutionized the way people viewed the cosmos by turning a spyglass to the heavens. With his rudimentary telescope, he had trouble making out the rings of Saturn that are visible with the most basic telescopes we have today. Throughout the years, advances in optics improved scientists' views of the planets, stars, and distant galaxies, but Earth's atmosphere still blocked much of the light for ground-based observers.

It wasn't until 1923 that the idea of space telescopes was first proposed. German scientist Hermann Oberth suggested that a telescope could be launched into orbit in order to overcome



The Hubble Space Telescope exits the cargo bay of Discovery during its deployment on April 25, 1990. Credit: NASA

An STS-125 crew member aboard the Space Shuttle Atlantis captured this image of the Hubble Space Telescope as the two spacecraft continue their relative separation on May 19, after having been linked together for the better part of a week to complete the final servicing mission for the orbital observatory. Credit: NASA

atmospheric distortions. As rocket launchings became more frequent, the idea became feasible, and in 1969, official approval was given for the launch of a large space telescope. However, its development took longer than preparing for a trip to the moon.

A few years later, in 1975, the European Space Agency (ESA) collaborated with NASA on a plan that would eventually become Hubble. Funding was approved by Congress approved in 1977, and with the development of the Space Shuttle, NASA now had a means to deliver the telescope to orbit.

Originally dubbed the Large Space Telescope, it was later renamed the Hubble Space Telescope (HST) in honor of Edwin Hubble, the American astronomer who determined that the universe was expanding. On April 24, 1990, world's first space telescope was then launched aboard the Space Shuttle Discovery. The development and construction of Hubble originally cost $1.5 billion, but there would be ongoing costs – both expected and unexpected.

With the very first observation, researchers noticed an issue – the telescope's images were fuzzy. Hubble's main mirror had a major defect: a spherical aberration, a fraction of the diameter of a single human hair, caused by a manufacturing error. Hubble was effectively near sighted. Researchers worked quickly to develop a fix.

However, it would be three years before NASA could undertake a repair mission. On Dec. 2, 1993, the Space Shuttle Endeavor ferried a crew of seven astronauts to fix Hubble across five days of spacewalks. During the missions two new cameras, including the Wide-Field Planetary Camera 2 (WFPC-2) were installed. When the first new images from Hubble reached Earth, they were breathtaking.

Images of the spiral galaxy Messier 100 demonstrate the improvement in Hubble images after corrective optics were installed during Servicing Mission 1 in 1993. Credit: NASA

Hubble has been serviced a total of five times. Among the repairs, astronauts had to replace batteries and directional gyroscopes. The final servicing mission took place in 2009, and the telescope is expected to continue to function for years to come. NASA is currently developing Hubble's replacement, the James Webb Space Telescope (JWST), which is scheduled to launch in 2018.

The Hubble Space Telescope's elevated perspective and advanced optics allow it to peer farther away than ground-based optics can dream of. Because light takes time to travel long distances, the range of the HST makes it function like a time machine. Looking through the orbiting telescope is like peering back in time; the light collected from remote objects shows the object as it appeared when the light left, not how it would appear today. Take our closest neighbor, the Andromeda galaxy -- at a distance of 2.5 million light-years from Earth we see it as it was 2.5 million years ago.

1. The Hubble Space Telescope (HST) early during its construction.

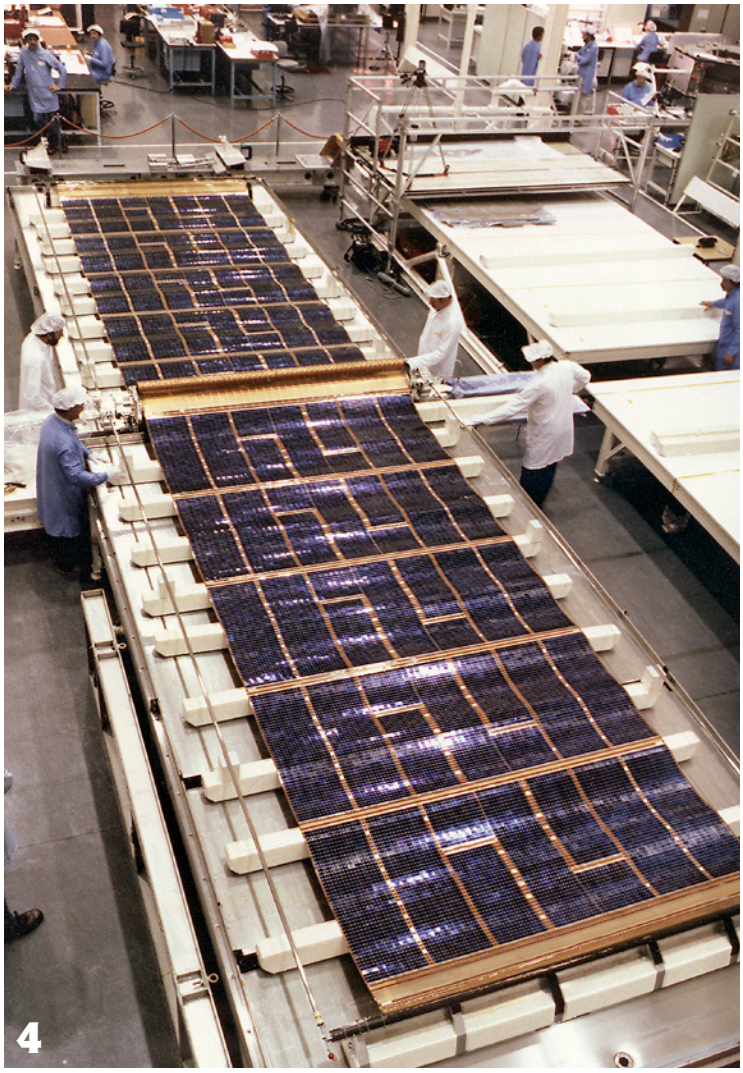
2. Workers study Hubble's main, eight-foot (2.4 m) mirror. Hubble, like all telescopes, plays a kind of pinball game with light to force it to go where scientists need it to go. When light enters Hubble, it reflects off the main mirror and strikes a second, smaller mirror. The light bounces back again, this time through a two-foot (0.6 m) hole in the center of the main mirror, beyond which Hubble's science instruments wait to capture it. In this photo, the hole is covered up.

3. Hubble being transferred from the Vertical Assembly Test Area to the High Bay at the Lockheed assembly plant in Sunnyvale, California in preparation for transport to the Kennedy Space Center after final testing and verification.

4. A solar cell blanket deployed on a water table during the Solar Array deployment test. The Hubble Solar Arrays provide power to the spacecraft. The arrays are mounted on opposite sides of the HST, on the forward shell of the Support Systems Module. Each array stands on a 4-foot mast that supports a retractable wing of solar panels 40-feet (12.1-meters) long and 8.2-feet (2.5-meters) wide, in full extension. The arrays rotate so that the solar cells face the Sun as much as possible to harness the Sun's energy. The Space Telescope Operations Control Center at the Goddard Space Center operates the array, extending the panels and maneuvering the spacecraft to focus maximum sunlight on the arrays. The HST Solar Array was designed by the European Space Agency and built by British Aerospace.

5. Hubble's Primary Mirror being ground at the Perkin-Elmer's optics fabrication facility in Connecticut. Once the 8-foot diameter mirror was ground to shape and polished, the glass surface was coated with a reflective layer of aluminum and a protective layer of magnesium fluoride.

6. Engineers in a clean room at Ball Aerospace in Boulder, Colo., work on one of Hubble's instruments, the Space Telescope Imaging Spectrograph (STIS). The instrument, installed in Hubble in 1997, breaks light into colors, giving scientists an important analytical tool for studying the cosmos. STIS has been used to study such objects as black holes, new stars, and massive planets forming outside our solar system.

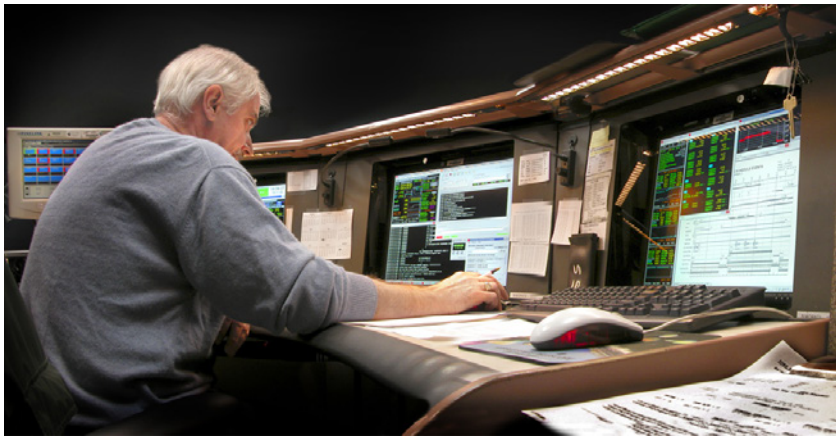


Thanks to Hubble's optics, we can see distant objects that otherwise wouldn't be visible.

Astronomers pointed the HST to a seemingly-empty patch of sky, and were surprised with what they saw. The "empty" patch of sky contained over 3,000 galaxies too distant to be viewed by other telescopes. Subsequent deep field observations have yielded even more information, and never-before seen views.

In addition to gazing at the early universe, Hubble has helped astronomers determine the age of the universe. By measuring a special kind of pulsing star known as a Cepheid variable, astronomers were able to narrow down the age of the universe from the pre-HST range of 10 to 20 billion years, to the more precise 13.7 billion year age.

The Hubble Space Telescope is also capable of examining individual stars across various stages of their evolution – from the clouds of dust that form the embryonic stellar cocoons to the corpses of stars that went supernova, and every stage in between.



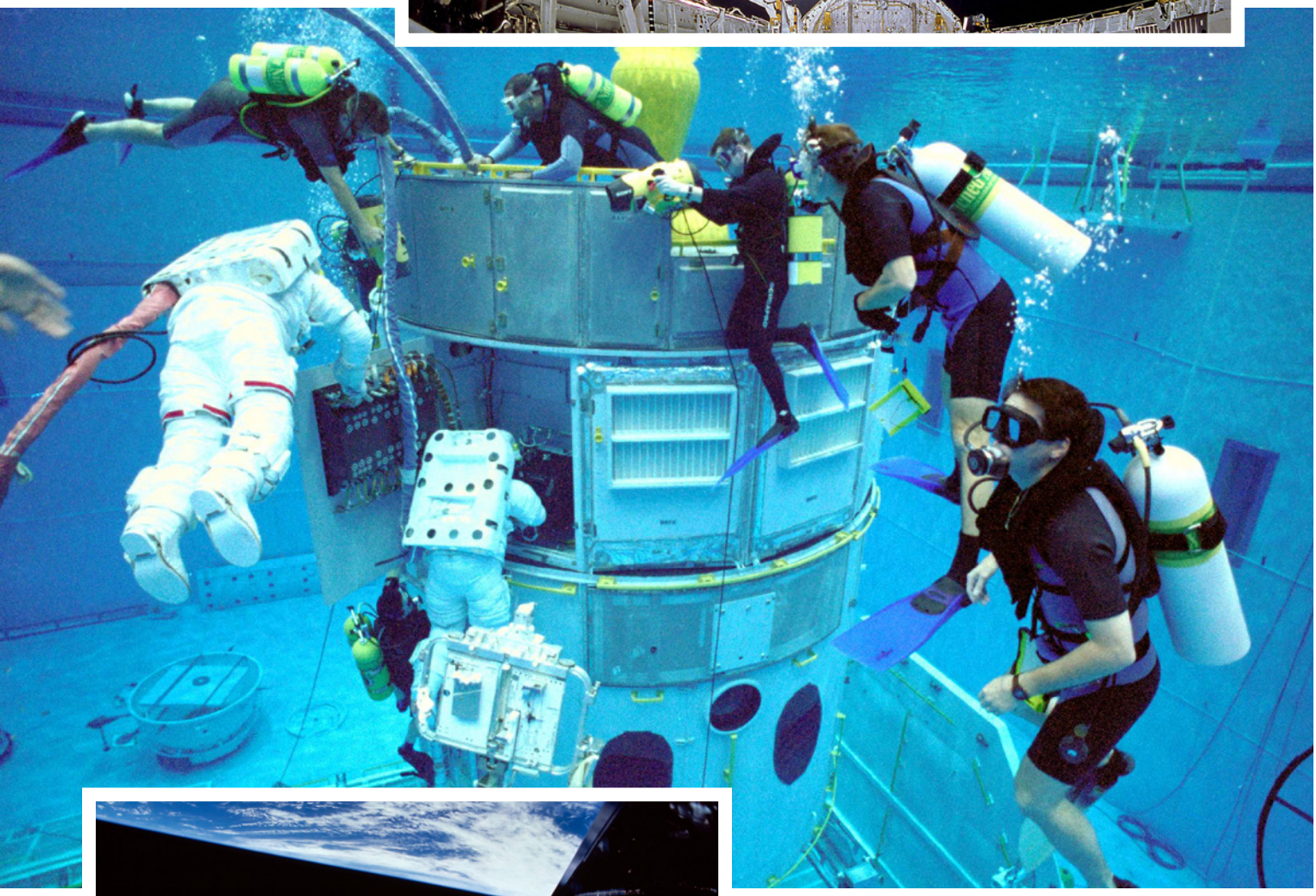
At Hubble's control center at the Space Telescope Science Institute in Baltimore, Md., Larry Stake monitors Hubble operations. All the commands transmitted to Hubble, including the instructions on recording scientific data and orders on which stars to observe, come from here. Hubble is monitored constantly by four teams, each made up of a quartet of flight controllers. Credit: STScI

Stars in other galaxies are fairly easy to see, but the planets orbiting them present a challenge. The idea of extra-solar planets, or exoplanets, used to be a thing of science fiction; however, in 2008, Hubble captured pictures of the planet Fomalhaut b --the first exoplanet directly imaged in visible light. Most planets are challenging to photograph, and most of Hubble's exoplanet discoveries were not directly imaged. The transiting method of exoplanet detection is made by the detection of a dip in the host star's brightness as the planet passes in front.

Hubble may spend much of its time peering light-years from Earth, but occasionally will be used to photograph the planets in our own solar system. High resolution images taken of Jupiter, Saturn, and even Pluto can provide insights that can only be topped by planetary probes in orbit around them. Images from Hubble allow scientists on Earth to monitor changes in the planet's atmosphere and surface. When the comet Shoemaker-Levy crashed into the Jupiter in 1994, Hubble photographed the fatal collision. Recently, Hubble detected a possible sub-surface ocean in the Jovian moon Ganymede.

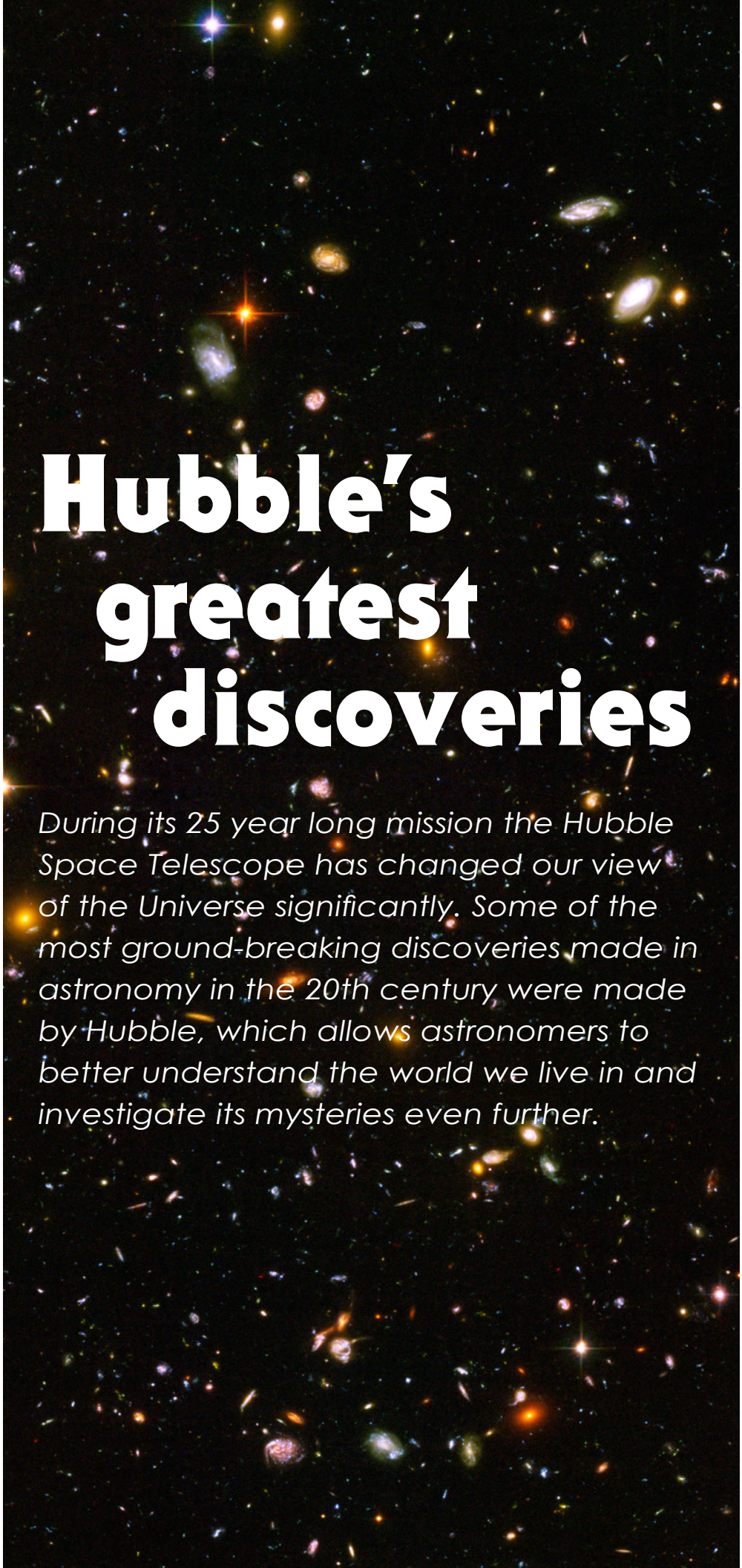
Despite its turbulent beginning, the Hubble Space Telescope has been operating for a quarter of a century, providing scientists with a greater understanding of the universe as a whole. Hard to fathom that children today have lived in a world that's always contained the Hubble Space Telescope.

The IMAX Cargo Bay Camera view of the Hubble Space Telescope (right) at the moment of release from Space Shuttle Discovcery during the STS-31 mission. Credit: NASA



Astronauts train to service Hubble (above) in a huge, water-filled tank that simulates weightlessness. The 40-foot-deep (12 m) tank at NASA's Johnson Space Center contains full-scale underwater mockups of Hubble, its instruments, and the carriers that hold the instruments. The astronauts wear pressurized suits similar to those they wear in orbit. Credit: NASA

NASA astronaut Story Musgrave (left) near the top of the Hubble Space Telescope during the final EVA of STS-61. Credit: NASA



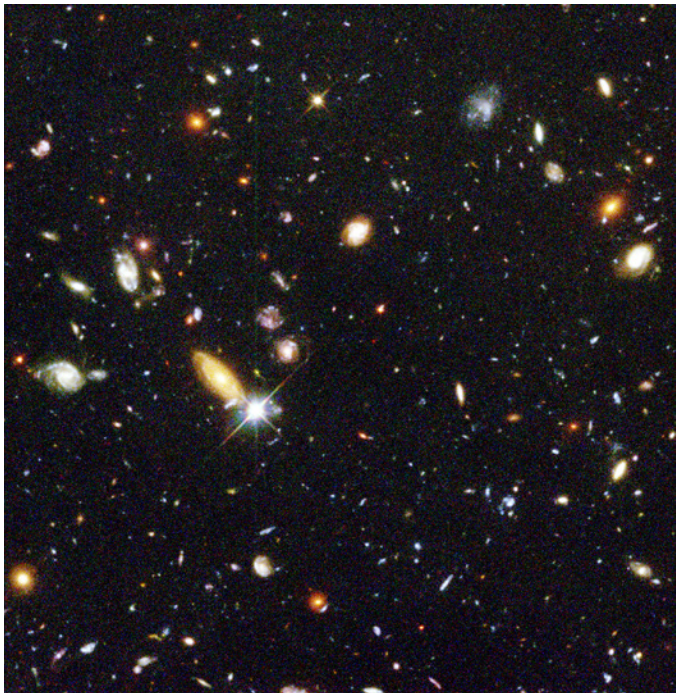
Hubble's greatest discoveries

During its 25 year long mission the Hubble Space Telescope has changed our view of the Universe significantly. Some of the most ground-breaking discoveries made in astronomy in the 20th century were made by Hubble, which allows astronomers to better understand the world we live in and investigate its mysteries even further.

The Hubble Deep Fields:

How Hubble has observed the furthest away galaxies and the most ancient starlight ever seen by humankind

One of the main scientific justifications for building Hubble was to measure the size and age of the Universe and test theories about its origin. Images of faint galaxies give "fossil" clues as to how the Universe looked in the remote past and how it may have evolved with time. The Deep Fields gave astronomers the first really clear look back to the time when galaxies were forming. The first deep fields — Hubble Deep Field North and South — gave astronomers a peephole to the ancient Universe for the first time, and caused a real revolution in modern astronomy.



Representing a narrow "keyhole" view of the universe, the original Hubble Deep Field image covers a speck of the sky only about the width of a dime 75 feet away. Credit: Robert Williams, Hubble Deep Field Team (STScI), NASA

Subsequent deep imagery from Hubble, including the Hubble Ultra Deep Field, has revealed the most distant galaxies ever observed. Because of the time it has taken their light to reach us, we see some of these galaxies as they were just half a billion years after the Big Bang.

Deep field observations are long-lasting observations of a particular region of the sky intended to reveal faint objects by collecting the light from them for an appropriately long time. The 'deeper' the observation is (i.e. longer exposure time), the fainter are the objects that become visible on the images. Astronomical objects can either look faint because their natural brightness is low, or because of their distance. In the case of the Hubble Deep and Ultra Deep Fields, it is the extreme distances involved which make them faint, and hence make observations challenging.

Using the different Hubble Deep fields astronomers were able to study young galaxies in the early Universe _and the most distant primeval galaxies. The different deep fields are also a good gathering grounds to find the most distant objects ever observed.

Within 2012 and 2014 Hubble created two new deep fields: The Hubble eXtreme Deep Field is so far the deepest image ever taken of the sky so far and combines the light of one million seconds of observation. The last Hubble Ultra Deep Field released in 2014 was observed in ultraviolet. This image allowed astronomers to study star formation in a region 5 to 10 light- years away from us.

Age and size of the Universe:

How Hubble has calculated the age of the cosmos and discovered the Universe is expanding at an ever faster rate

The top ranked scientific justification for building Hubble was to determine the size and age of the Universe through observations of Cepheid variables. The periodic brightness variations of these stars depends on physical properties of the stars such as their mass and true brightness. This means that astronomers, just by looking at the variability of their light, can find out about the Cepheids' physical nature, which then can be used to determine their distance.

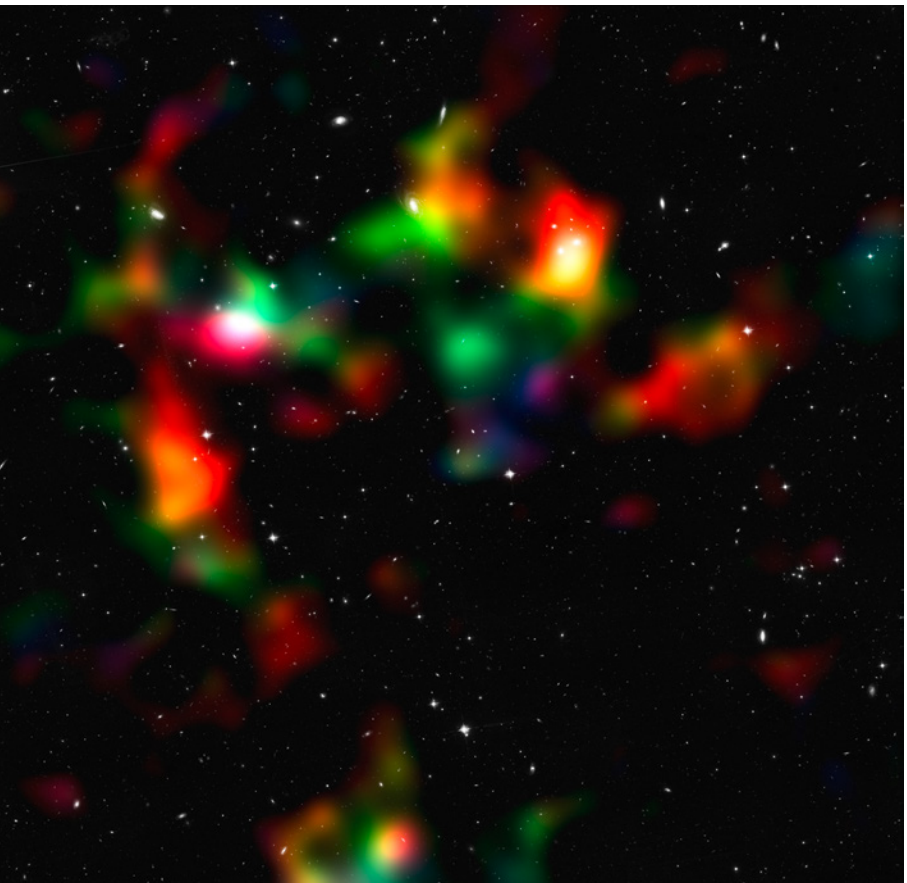
Astronomers have used Hubble to observe Cepheids with extraordinary results. The Cepheids have then been used as stepping-stones to make distance measurements for supernovae, which have, in turn, given a measure for the scale of the Universe. Today we know the age of the Universe to a much higher precision than before Hubble: around 13.7 billion years.

The expansion of the Universe

Another purposes of Hubble was to determine the rate of expansion of the Universe, known as the Hubble Constant. After eight years of Cepheid observations this work was concluded by finding that the expansion increases with 70 km/second for every 3.26 million light-years you look further out into space.

For many years cosmologists have discussed whether the expansion of the Universe would stop in some distant future or continue ever more slowly. The observations of distant supernovae made by Hubble indicate that the expansion is nowhere near slowing down. In fact, due to some mysterious property of space itself, called dark energy, the expansion is accelerating. This surprising conclusion came from combined measurements of remote supernovae with most of the world's top-class telescopes, including Hubble.

The discovery of the accelerating expansion of the Universe led to three astronomers, Saul Perlmutter, Adam Riess and Brian Schmidt, being awarded the 2011 Nobel Prize in Physics.



This image shows a smoothed reconstruction of the total (mostly dark) matter distribution in the COSMOS field, created from data taken by the Hubble Space Telescope and ground-based telescopes. It was inferred from the weak gravitational lensing distortions that are imprinted onto the shapes of background galaxies. The colour coding indicates the distance of the foreground mass concentrations as gathered from the weak lensing effect. Structures shown in white, cyan, and green are typically closer to us than those indicated in orange and red. To improve the resolution of the map, data from galaxies both with and without redshift information were used.

The new study presents the most comprehensive analysis of data from the COSMOS survey. The researchers have, for the first time ever, used Hubble and the natural "weak lenses" in space to characterise the accelerated expansion of the Universe.

Credit: NASA, ESA, P. Simon (University of Bonn) and T. Schrabback (Leiden Observatory)

The lives of stars:

How Hubble has revolutionised our understanding of the birth and death of stars

Most of the light and radiation we can observe in the Universe originates in stars — individual stars, clusters of stars, nebulae lit by stars and galaxies composed of billions of stars. Like human beings stars are born, mature and eventually die. Hubble has gone beyond what can be achieved by other observatories by linking together studies of the births, lives and deaths of individual stars with theories of stellar evolution.

In particular Hubble's ability to probe stars in other galaxies enables scientists to investigate the influence of different environments on the lives of stars. This is crucial in order to be able to complement our understanding of the Milky Way galaxy with that of other galaxies.

Uncovering the Galaxy's stellar nurseries

Hubble's work allowed it to link star formation with stellar evolution. Its infrared instruments are capable of looking through the dust clouds surrounding newly born stars. Some of the most surprising discoveries so far have come about by peering through the clouds of dust surrounding the centre of our Milky Way. Astronomers found that this centre, which was thought to be a calm and almost dead region, is in fact populated with massive infant stars gathered into clusters.

Stellar skeletons

The last phases of solar-like stars have been investigated through observations of planetary nebulae and proto-planetary nebulae. These are colourful shells of gas expelled into space by dying stars. The varying shapes and colours of these intricate structures with different colours tracing different, often newly created, chemical elements, have shown that the final stages of the lives of stars are more complex than once thought and there also seems to exit a bizarre alignment of planetary nebula.

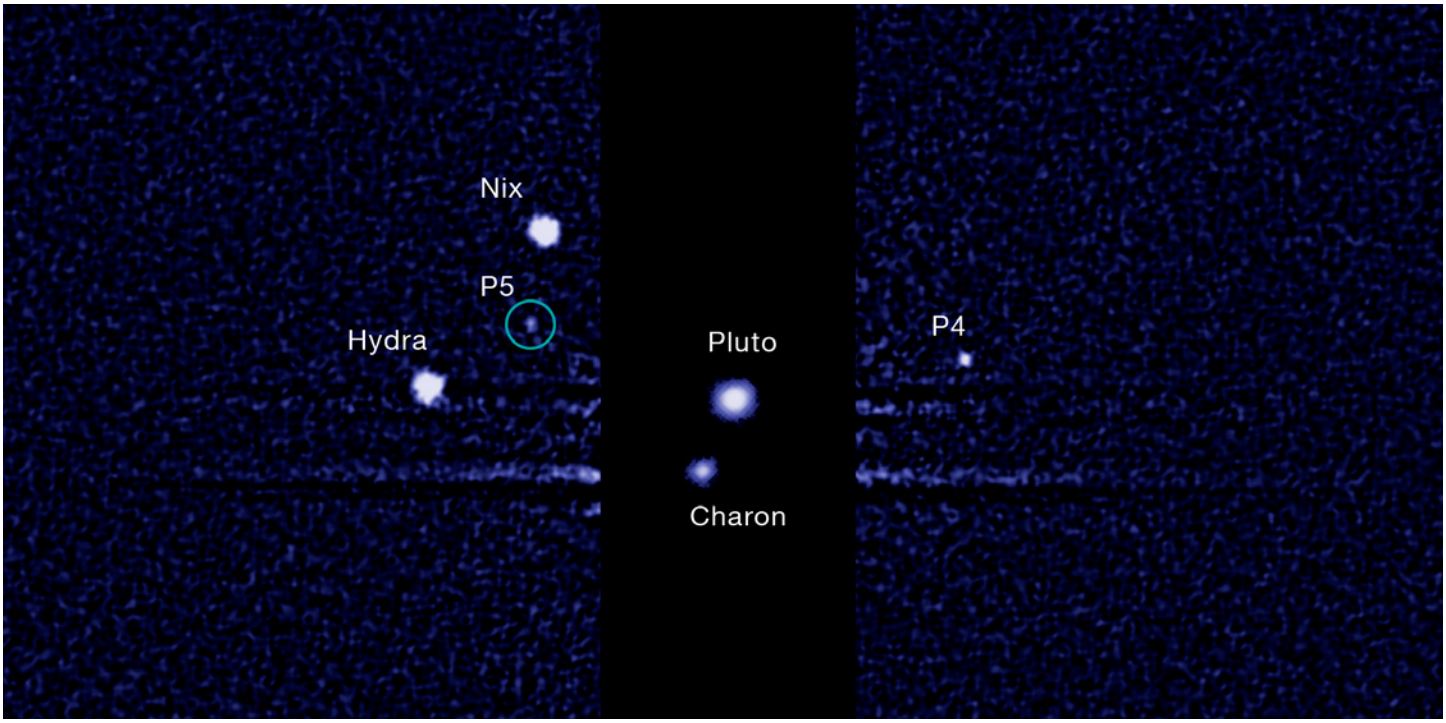
This image of NGC 2440 shows the colourful "last hurrah" of a star like our Sun. The star is ending its life by casting off its outer layers of gas, which formed a cocoon around the star's remaining core. Ultraviolet light from the dying star makes the material glow. The burned-out star, called a white dwarf, is the white dot in the centre. Credit: NASA, ESA, and K. Noll (STScI)

Gamma Ray Bursts

Gamma Ray Bursts emit very intense gamma-ray radiation for short periods and are observed a few times per day by special gamma-ray detectors on observatories in space. Today, partly due to Hubble, we know that these bursts originate in other galaxies — often at very large distances.

Their origin has eluded scientists for a long time, but, after Hubble observations of the atypical supernova SN1998bw and the Gamma Ray Burst GRB 980425 a physical connection of these became probable.

An unusual burst of radiation detected in early 2011 may tell a different story: rather than a star ending its life in a supernova, this burst may be evidence of a star being ripped apart as it falls into a supermassive black hole. If confirmed by further observations, this would be the first time this phenomenon has ever been spotted.



A team of astronomers using the NASA/ESA Hubble Space Telescope has discovered a fifth moon orbiting the icy dwarf planet Pluto. The green circle marks the newly discovered moon, designated S/2012 (134340) 1, or P5, as photographed by Hubble's Wide Field Camera 3 on 7 July 2012. The moon is estimated to be 10 to 25 kilometres across. The darker stripe in the centre of the image is because the picture is constructed from a long exposure designed to capture the comparatively faint satellites of Nix, Hydra, P4 and S/2012 (134340) 1, and a shorter exposure to capture Pluto and Charon, which are much brighter.
Credit: NASA, ESA, and M. Showalter (SETI Institute)

The solar neighbourhood:

What Hubble has taught us about planets, asteroids and comets in our own Solar System

Hubble's high resolution images of the planets and moons in our Solar System can only be surpassed by pictures taken from spacecraft that actually visit them. Hubble even has one advantage over these probes: it can look at these objects periodically and so observe them over much longer periods than any passing probe could. Regular monitoring of planetary surfaces is vital in the study of planetary atmospheres and geology, where evolving weather patterns such as dust storms can reveal much about the underlying processes.

In comparison with probes that have to travel vast distances and require years of planning to visit the planets Hubble is also able to react quickly to sudden dramatic events occurring in the Solar System. This allowed it to witness the stunning plunge of comet Shoemaker-Levy 9 into Jupiter's atmosphere during the period 16-22 July 1994. Hubble followed the comet fragments on their last journey and delivered incredible high-resolution images of the impact scars. The consequences of the impact could be seen for several days afterwards, and by studying the Hubble data astronomers were able to gain fundamental information about the composition and density of the giant planet's atmosphere. Since the impact of Shoemaker-Levy 9, Hubble has continued to study impacts and events on Jupiter, improving our understanding of the Solar System's largest planet.

Pluto and its surrounding moons have also been the target of Hubble's observations. Several new moons have been discovered as well as a dwarf planet beyond Pluto, which led to the discussion of Pluto being a planet.

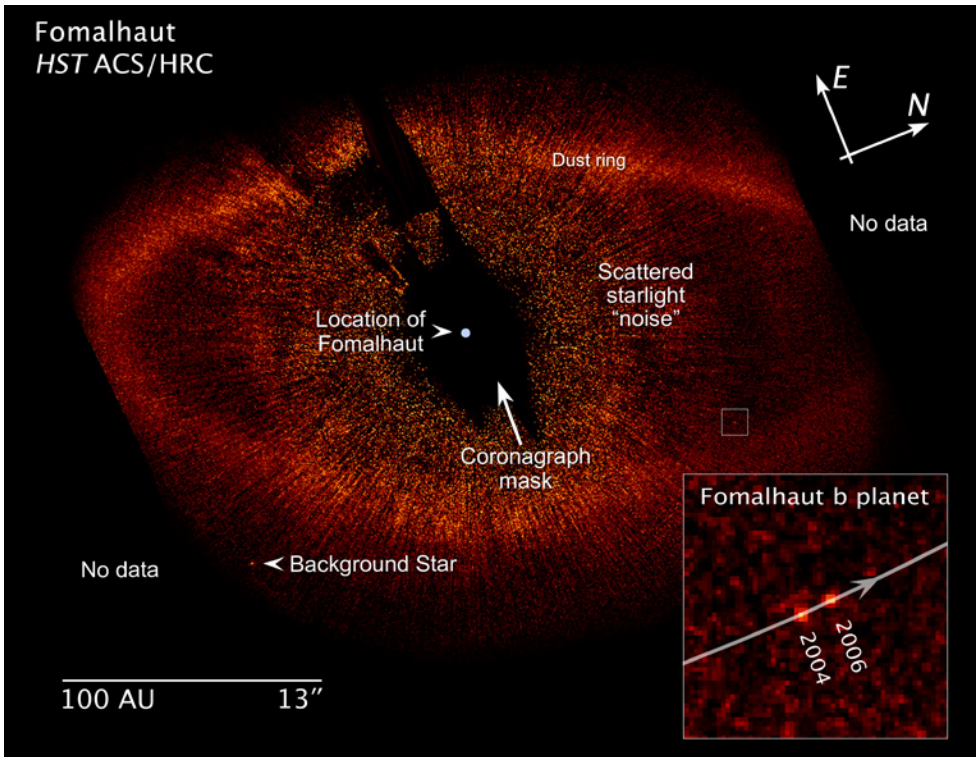
Hubble also observed the spectacular break up of comet 73P/Schwassmann-Wachmann 3 as it visited the inner Solar System, the asteroid collision P2010/A2 and a mysterious disintegrating asteroid.

Exoplanets and proto-planetary discs:

How Hubble has made the first ever image of an exoplanet in visible light, and spotted planetary systems as they form

Hubble's high resolution has been indispensable in the investigation of the gas and dust disks, dubbed proplyds, around the newly born stars in the Orion Nebula. The proplyds may very well be young planetary systems in the early stages of creation. Also thanks to Hubble we have visual proof today that dusty disks around young stars are common.

The first detection of an atmosphere around an extrasolar planet was seen in a gas-giant planet orbiting the Sun-like star HD 209458, 150 light-years from Earth. The presence of sodium as well as evaporating hydrogen, oxygen and carbon was detected in light filtered through the planet's atmosphere when it passed in front of its star as seen from Earth. The details revealed by Hubble are superior to anything seen to date with ground-based instruments.



This annotated image shows key features of the Fomalhaut system, including the newly discovered planet Fomalhaut b, and the dust ring. Also included are a distance scale and an insert, showing how the planet has moved around its parent star over the course of 21 months. The Fomalhaut system is located approximately 25 light-years from the Earth. Credit: NASA, ESA, and Z. Levay (STScI)

Hubble has been instrumental in studying these extra-solar planets but it has also helped to detect them as well. In 2008, Hubble made an image of the planet Fomalhaut b, a gas giant planet about three times the mass of Jupiter, which orbits the star Fomalhaut. This was the first ever image made of an exoplanet in visible light. Within the same year the first organic molecule on an extrasolar planet was detected by Hubble.

In 2012 Hubble even discovered a complete new type of extra-solar planet: a water world enshrouded by a thick, steamy atmosphere. Later Hubble was able to measure for the first time the colour and to create the most detailed weather map an exoplanet.

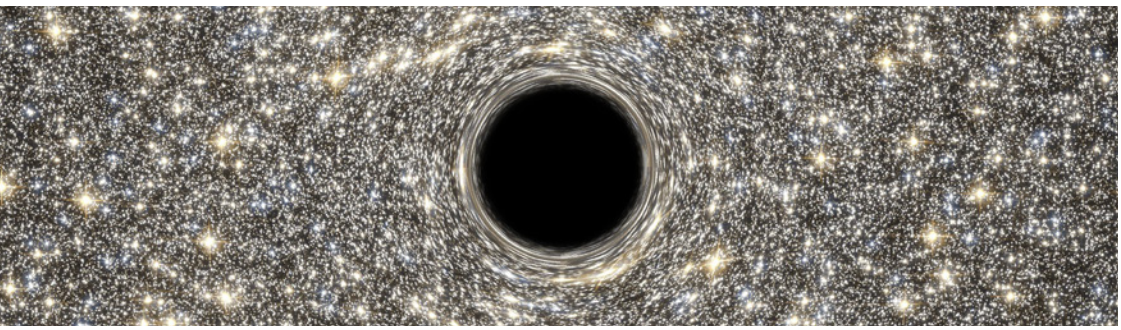
Black holes, quasars, and active galaxies:

How Hubble found black holes at the heart of all large galaxies

Black holes are objects so dense, and with so much mass, that even light cannot escape their gravity. It is in the study of supermassive black holes that Hubble has made its biggest contribution.

It is impossible to observe black holes directly, and astronomers had no way to test their theories until Hubble started its work. The high resolution of Hubble made it possible to see the effects of the gravitational attraction of some of these objects on their surroundings. Hubble has also proved that supermassive black holes are most likely present at the centres of most, if not all, large galaxies. This has important implications for the theories of galaxy formation and evolution.

Black holes have effects on their surroundings. These include powerful jets of electrons that travel many thousands of light years from the centres of the galaxies. Matter falling towards a black hole can also be seen emitting bright light and if the speed of this falling matter can be measured, it is possible to determine the mass of the black hole itself. This is not an easy task and it requires the extraordinary capabilities of Hubble to carry out these sophisticated measurements. Hubble observations have been fundamental in the study of the jets and discs of matter around a number of black holes. Accurate measurements of the masses have been possible for the first time. Hubble has found black holes 3 billion times as massive as our Sun at the centre of some galaxies. While this might have been expected, Hubble has surprised everyone by providing strong evidence that black holes exist at the centres of all large and even small galaxies. Hubble also managed not only to observe the jets created by black holes but also the glowing discs of material surrounding a supermassive black hole.



This is an illustration of the supermassive black hole located in the middle of the very dense galaxy M60-UCD1. Because no light can escape from the black hole, it appears simply in silhouette against the starry background. The black hole's intense gravitational field warps the light of the background stars to form ring-like images just outside the dark edges of the black hole's event horizon.
Credit: NASA, ESA, D. Coe, G. Bacon (STScI)

Furthermore, it appears that larger galaxies are the hosts of larger black holes. There must be some mechanism that links the formation of the galaxy to that of its black hole and vice versa. This has profound implications for theories of galaxy formation and evolution and is an ongoing area of research in astronomy.

Black holes and the quasar connection

Before Hubble, quasars were considered to be isolated star-like objects of a mysterious nature. Hubble has observed several quasars and found that they all reside at galactic centres. Today most scientists believe that supermassive black holes at the galactic centres are the "engines" that power the quasars. They also believe that quasars, radio galaxies and the centres of so-called active galaxies just are different views of more or less the same phenomenon: a black hole with energetic jets beaming out from two sides. When the beam is directed towards us we see the bright lighthouse of a quasar. When the orientation of the system is different we observe it as an active galaxy or a radio galaxy. This unified model has gained considerable support through a number of Hubble observational programmes.

Formation of stars:

How Hubble observes stars as they form from huge dust clouds

The important clues about star formation lie hidden behind the veil of the dusty, and often very beautiful, star forming molecular clouds. Astronomers turn their eyes to the birth of other stars and stellar systems in neighbouring stellar 'maternity wards' and use these to see a re-play of the events that created our own Solar System.

Inside the Orion Nebula

The large mosaic of 15 Hubble images showing the central part of the Orion complex is one of the most detailed images of a star forming region ever made.

Peering through dust

Dust clouds scatter visible light, but let infrared light through unimpeded, meaning infrared observations are often the only way to see young stars. During the servicing mission in 2009 the Wide Field Camera 3 (WFC3) was installed. An instrument designed to make detailed images both in visible light and in infrared. The WFC3 offers greatly improved capabilities in the infrared compared to what was possible before.

WFC3's images of the Carina Nebula made in visible light show dense clouds of dust and gas. But the images taken by the camera of the same region in infrared make the dust fade, leaving just a faint outline of its location. The young stars forming inside the cloud are suddenly revealed.

This is a series of close-up views of the complex gas structures in a small portion of the Carina Nebula. The nebula is a cold cloud of predominantly hydrogen gas. It is laced with dust, which makes the cloud opaque. The cloud is being eroded by a gusher of ultraviolet light from young stars in the region. They sculpt a variety of fantasy shapes, many forming tadpole-like structures. In some frames, smaller pieces of nebulosity can be seen freely drifting, such as the structure, four trillion kilometres long, at upper right. The most striking feature is a horizontal jet 5.5 trillion kilometres long in the upper left frame. It is being blasted into space by a young star hidden in the tip of the pillar-like structure. A bowshock has formed near the tip of the jet.
Credit: NASA, ESA, M. Livio and the Hubble 20th Anniversary Team (STScI)

Star formation and the history of the cosmos

Hubble has also contributed to our understanding of star formation beyond the confines of the Milky Way. Neither Hubble nor any other telescope is able to see individual stars outside of the Milky Way and a handful of nearby galaxies. However, the telescope has contributed to major discoveries about star formation in the far reaches of the Universe. Studying starlight from the most distant objects Hubble has observed gives clues about how stars formed in the early years of the Universe, and how they have changed over time.

Hubble discoveries in the field of star formation in the early Universe include the realisation that stars and galaxies formed earlier in cosmic history than previously thought.

Composition of the Universe:

How Hubble studied what the Universe is made of, and came to some startling conclusions

All over the Universe stars work as giant reprocessing plants taking light chemical elements and transforming them into heavier ones. The original, primordial, composition of the Universe is studied in such fine detail because it is one of the keys to our understanding of processes in the very early Universe.

Astronomers investigated the nature of the gaseous matter that fills the vast volume of intergalactic space. By observing ultraviolet light from a distant quasar, which would otherwise have been absorbed by the Earth's atmosphere, scientists found the long-sought signature of helium in the early Universe. This was an important piece of supporting evidence for the Big Bang theory. It also confirmed scientists' expectation that, in the very early Universe, matter not yet locked up in stars and galaxies was nearly completely ionised (the atoms were stripped of their electrons). This was an important step forward for cosmology.

Dark Matter

Today astronomers believe that around three quarters of the mass of the Universe consists of dark matter, a substance quite different from the normal matter that makes up the familiar world around us. Hubble has played an important part in work intended to establish the amount of dark matter in the Universe and to determine where it is.

The riddle of what the ghostly dark matter is made of is still far from solved, but Hubble's incredibly sharp observations of gravitational lenses have provided stepping stones for future work in this area. Dark matter only interacts with gravity, which means it neither reflects, emits nor obstructs light. Because of this, it cannot be observed directly. However, Hubble studies of how clusters of galaxies bend the light that passes through them lets astronomers deduce where the hidden mass lies. This means that they are able to make maps of where the dark matter lies in a cluster.

One of Hubble's big breakthroughs in this area is the discovery of how dark matter behaves when clusters collide with each other. Studies of a number of these clusters have shown that the location of dark matter does not match the distribution of hot gas. This strongly supports theories about dark matter: we expect hot gases to slow down as they hit each other and the pressure increases. Dark matter, on the other hand, should not experience friction or pressure, so we would expect it to pass through the collision relatively unhindered. Hubble and Chandra observations have indeed confirmed that this is the case.

A 3D map of the dark matter distribution in the Universe

In 2007 an international team of astronomers used Hubble to create the first three-dimensional map of the large-scale distribution of dark matter in the Universe. It was constructed by measuring the shapes of half a million galaxies observed by Hubble. The light of these galaxies travelled — until it reached Hubble — down a path interrupted by clumps of dark matter which deformed the appearance of the galaxies. Astronomers used the observed distortion of the galaxies shapes to reconstruct their original shape and could therefore also calculate the distribution of dark matter in between.

This map showed that normal matter, largely in the form of galaxies, accumulates along the densest concentrations of dark matter. The created map stretches halfway back to the beginning of the Universe and shows how dark matter grew increasingly clumpy as it collapsed under gravity. Mapping dark matter distribution down to even smaller scales is fundamental for our understanding of how galaxies grew and clustered over billions of years. Tracing the growth of clustering in dark matter may eventually also shed light on dark energy.

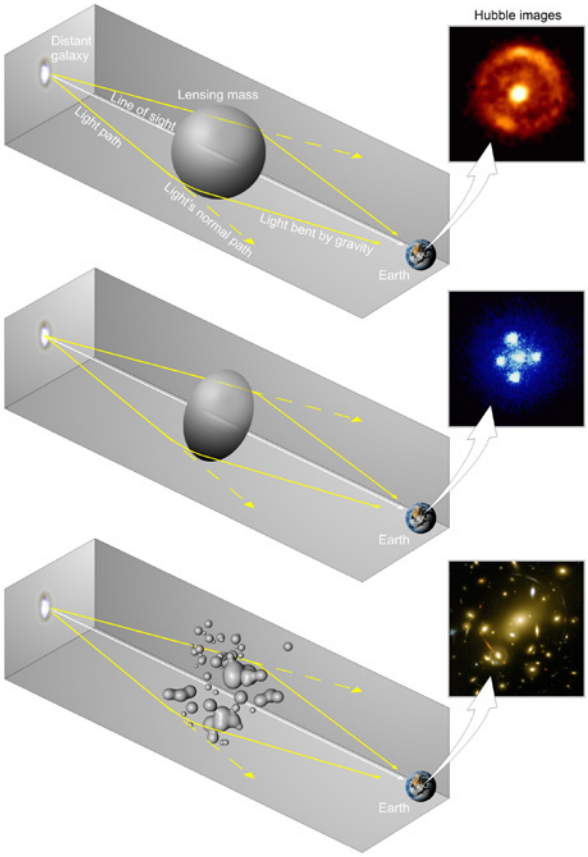
Dark energy

More intriguing still than dark matter is dark energy. Hubble studies of the expansion rate of the Universe have found that the expansion is actually speeding up. Astronomers have explained this using the theory of dark energy, as a sort of negative gravity that pushes the Universe apart ever faster. Studies of the rate of expansion of the cosmos suggests that dark energy is by far the largest part of the Universe's mass-energy content, far outweighing both normal matter and dark matter. While astronomers have been able to take steps along the path to understanding how dark energy works and what it does, its true nature is still a mystery.

Gravitational lenses:

How astronomers use a helping hand from Einstein to increase Hubble's range

Light does not always travel in straight lines. Einstein predicted in his Theory of General Relativity that massive objects will deform the fabric of space itself. When light passes one of these objects, such as a cluster of galaxies, its path is changed slightly. This effect, called gravitational lensing, is only visible in rare cases and only the best telescopes can observe the related phenomena. Hubble's sensitivity and high resolution allow it to see faint and distant gravitational lenses that cannot be detected with ground-based telescopes. The gravitational lensing results in multiple images of the original galaxy each with a characteristically distorted banana-like shape or even into rings.



Gravitational lenses produce different shaped images depending on the shape of the lensing body. If the lens is spherical then the image appears as an Einstein ring (in other words as a ring of light) (top); if the lens is elongated then the image is an Einstein cross (it appears split into four distinct images) (middle), and if the lens is a galaxy cluster, like Abell 2218, then arcs and arclets (banana-shaped images) of light are formed (bottom). Credit: European Space Agency

Hubble was the first telescope to resolve details within these multiple banana-shaped arcs. Its sharp vision can reveal the shape and internal structure of the lensed background galaxies directly and in this way one can easily match the different arcs coming from the same background object — be it a galaxy or even a supernova — by eye. Since the amount of lensing depends on the total mass of the cluster, gravitational lensing can be used to "weigh" clusters. This has considerably improved our understanding of the distribution of the dark matter in galaxy clusters and hence in the Universe as a whole. The effect of gravitational lensing also allowed a first step towards revealing the mystery of the dark energy.

As gravitational lenses function as magnification glasses it is possible to use them to study distant galaxies from the early Universe, which otherwise would be impossible to see.

Hubble's

Top 100

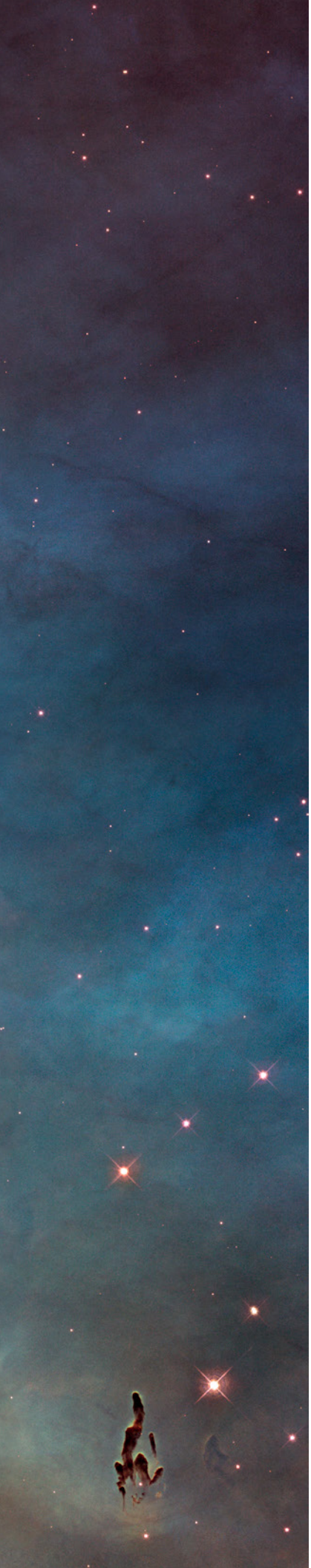
images

The Hubble Top 100 list is compiled, and regularly reviewed, by staff of ESA/Hubble (www.spacetelescope.org).

"No matter what Hubble reveals
— planets, dense star fields,
colorful interstellar nebulae,
deadly black holes,
graceful colliding galaxies,
the large-scale structure of the Universe
— each image establishes
your own private vista
on the cosmos."

— Neil deGrasse Tyson

Director of Hayden Planetarium
American Museum of Natural History
New York, New York



1 Pillars of Creation
(new view)

The NASA/ESA Hubble Space Telescope has revisited one of its most iconic and popular images: the Eagle Nebula's Pillars of Creation. This image shows the pillars as seen in visible light, capturing the multi-coloured glow of gas clouds, wispy tendrils of dark cosmic dust, and the rust-coloured elephants' trunks of the nebula's famous pillars.

The dust and gas in the pillars is seared by the intense radiation from young stars and eroded by strong winds from massive nearby stars. With these new images comes better contrast and a clearer view for astronomers to study how the structure of the pillars is changing over time.

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

"A lot of iconic Hubble images have shaped my career, from the Pillars of Creation [Original 1995 image is #82 on the Top 100 list] to the Hubble Ultra Deep field [#7]. It is no wonder that public is excited. Hubble offers far sharper and deepest views of our Universe. We are witnessing the birth of stars and galaxies like ours, to observations of dark matter and even dark energy.

"It will be a very sad day when Hubble goes. I want it to make one final look at the Pillars of Creation before it drifts away."

— Dr. Marusa Bradac

Associate Professor
University of California Davis

Editor's note: *For this commemorative issue, we asked a number of scientists to share their thoughts about the Hubble Space Telescope. Their responses are printed throughout this Top 100 list. Please note that the quotes are not always about the image sharing that page.*

2. A rose made of galaxies

This image of a pair of interacting galaxies called Arp 273 was released to celebrate the 21st anniversary of the launch of the Hubble Space Telescope.

The distorted shape of the larger of the two galaxies shows signs of tidal interactions with the smaller of the two. It is thought that the smaller galaxy has actually passed through the larger one

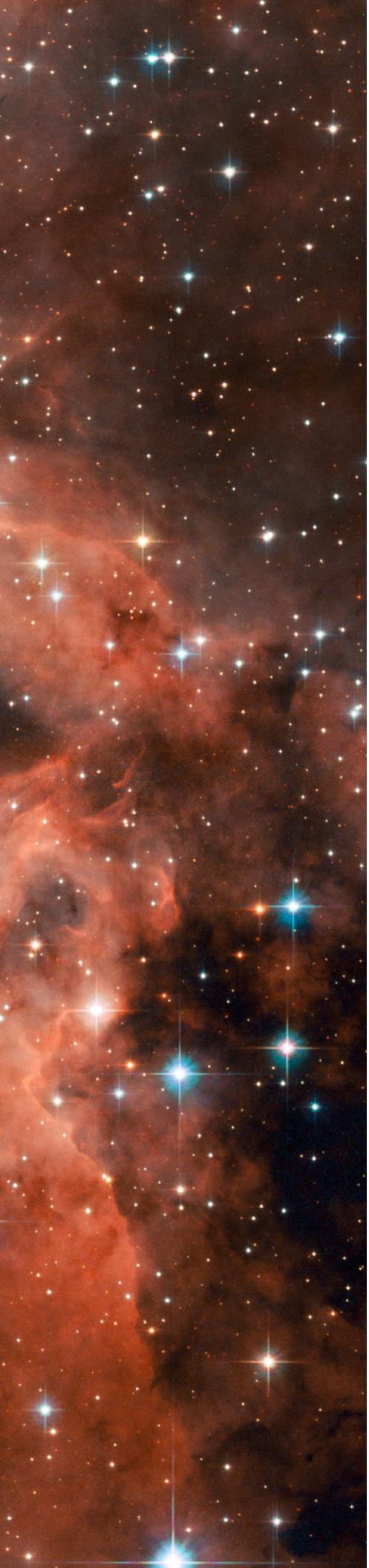
Credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA)

"A study by the University of Michigan found that a significant proportion of people shown a picture of a galaxy, taken with the Hubble Space Telescope, reported, 'images like this show how small and fragile planet Earth is in the context of the Universe.' People respond to Hubble's remarkable astronomical images: Hubble images trigger their intrinsic sense of wonder and satisfy their innate curiosity. As the New York Times wrote in 2002, 'The Hubble Space Telescope... has taught us to see properties of a universe humans have been able, for most of their history, to probe only with their thoughts.' Hubble has been a source of awe-inspiring images for a quarter of a century. Each year, Hubble's education programs reach over 500,000 pre-service and in-service teachers in the U.S., and over six million school children use Hubble material in their curricula. Science teachers across the nation can point to an image taken by the Hubble Space Telescope and say, 'only the United States can do this.' A 2013 survey of nearly 10,000 undergraduate engineering majors found that almost 1 in 5 identified 'work at NASA' as their dream job (Forbes, 6/12/2013), and Hubble is a big part of that.

"Hubble has become 'The People's Telescope,' and has explored our solar system and beyond with acuity, capability, and power. It is hard to imagine a world without Hubble, without the beauty that Hubble has brought, without the wonders that Hubble has shared. We are fortunate to have been witness to this amazing machine."

— Dr. Jim Green

Planetary Science Division Director
NASA Headquarters
Washington, D.C.



3. Extreme star cluster bursts into life

The star-forming region NGC 3603 - seen here in this Hubble image - contains one of the most impressive massive young star clusters in the Milky Way. Bathed in gas and dust the cluster formed in a huge rush of star formation thought to have occurred around a million years ago. The hot blue stars at the core are responsible for carving out a huge cavity in the gas seen to the right of the star cluster in NGC 3603's centre.

Credit: NASA, ESA and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration

"There's an art to making beautiful images from scientific data, and the Hubble team has mastered it. Hubble also came of age at the same time as the internet, which created a great opportunity to distribute large format, high resolution images that are absolutely stunning on computer desktops and screen savers. Before that most people only saw astronomy images published in books or newspapers.

"Hubble also had a fairly dramatic beginning, with the discovery of the flawed mirror and the subsequent mission where astronauts actually traveled to the telescope in order to repair it.

"It is our eye on the universe, but at the same time it is an actual object in space that we can visit and even touch, which helps to bring the images it produces a little closer to home."

— Dr. Heather Knutson

Assistant Professor of Planetary Science
California Institute of Technology
Pasadena, California

4 Antennae Galaxies reloaded

Hubble has snapped the best ever image of the Antennae Galaxies. Hubble has released images of these stunning galaxies twice before, once using observations from its Wide Field and Planetary Camera 2 (WFPC2) in 1997, and again in 2006 from the Advanced Camera for Surveys (ACS). Each of Hubble's images of the Antennae Galaxies has been better than the last, due to upgrades made during the famous servicing missions, the last of which took place in 2009.

The galaxies — also known as NGC 4038 and NGC 4039 — are locked in a deadly embrace. Once normal, sedate spiral galaxies like the Milky Way, the pair have spent the past few hundred million years sparring with one another. This clash is so violent that stars have been ripped from their host galaxies to form a streaming arc between the two. In wide-field images of the pair the reason for their name becomes clear — far-flung stars and streamers of gas stretch out into space, creating long tidal tails reminiscent of antennae.

This new image of the Antennae Galaxies shows obvious signs of chaos. Clouds of gas are seen in bright pink and red, surrounding the bright flashes of blue star-forming regions — some of which are partially obscured by dark patches of dust. The rate of star formation is so high that the Antennae Galaxies are said to be in a state of starburst, a period in which all of the gas within the galaxies is being used to form stars. This cannot last forever and neither can the separate galaxies; eventually the nuclei will coalesce, and the galaxies will begin their retirement together as one large elliptical galaxy.

Credit: ESA/Hubble & NASA

Visit Hubble here on Earth

Artifacts from the Hubble Space Telescope, and models of the telescope, may be viewed by the public at two locations.

At the Kennedy Space Center Visitors Complex in Florida, a high fidelity model of Hubble is displayed alongside Space Shuttle Atlantis.

Among the items on display at National Air and Space Museum on the National Mall in Washington, D.C., are:

- The Hubble Space Telescope Structural Dynamic Test Vehicle (SDTV), essentially a copy of the spacecraft used for testing everything from handling procedures to ensuring wiring harnesses bound for the flight vehicle fit properly.
- The Primary Mirror (flight spare), correctly polished
- An IMAX camera used by shuttle crew.
- The HST-PCU Trainer, used by astronauts on the ground to practice the difficult task of replacing the Power Control Unit during servicing mission
- The original Wide Field Planetary Camera 1 is also a part of the NASM collection, although it is not always on display.

5 Horsehead Nebula
(new infrared view)

This Hubble image, captured and released to celebrate the telescope's 23rd year in orbit, shows part of the sky in the constellation of Orion (The Hunter). Rising like a giant seahorse from turbulent waves of dust and gas is the Horsehead Nebula, otherwise known as Barnard 33.

This image shows the region in infrared light, which has longer wavelengths than visible light and can pierce through the dusty material that usually obscures the nebula's inner regions. The result is a rather ethereal and fragile-looking structure, made of delicate folds of gas — very different to the nebula's appearance in visible light.

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

"I am one of the professional astronomers from the generation that grew while the amazing pictures of Hubble were released. As a young girl I heard a talk in a planetarium about supernova, red giants, white dwarfs, black holes which I found extremely fascinating. This was just around the time that the Hubble was repaired and its first astonishing images were released to the public.

"In 1995 the Pillars of Creation [#82] was printed full page in one of the main Dutch newspapers that we read at home. I cut the picture from the newspaper and it must have been on my bedroom wall for many years after, until the paper started turning yellow. The image shows three immense beautiful dust pillars, surrounded by hot bright stars that are irradiating them. Deep inside these pillars new young stars and their planets are born.

"The images that Hubble released fascinated me. In fact, I found it extremely disappointing to go stargazing with an amateur telescope. It was nothing in comparison to the Hubble images. So, indirectly, Hubble demotivated me to become an observational astronomer. But I was extremely interested in trying to understand what the pictures depicted. Nearly 10 years later I started my Ph.D. in Theoretical Astrophysics studying the evolution of massive stars, and binary stars in particular."

— Dr. Selma E. de Mink

Assistant Professor
University of Amsterdam
Netherlands

6 Magnetic monster NGC 1275

This stunning image of NGC 1275 was taken using Hubble's Advanced Camera for Surveys in July and August 2006. It provides amazing detail and resolution of the fragile filamentary structures, which show up as a reddish lacy structure surrounding the central bright galaxy NGC 1275. These filaments are cool despite being surrounded by gas that is around 55 million degrees Celsius hot. They are suspended in a magnetic field which maintains their structure and demonstrates how energy from the central black hole is transferred to the surrounding gas.

By observing the filamentary structure, astronomers were, for the first time, able to estimate the magnetic field's strength. Using this information they demonstrated how the extragalactic magnetic fields have maintained the structure of the filaments against collapse caused by either gravitational forces or the violence of the surrounding cluster during their 100-million-year lifetime.

The filaments seen here can be a gaping 200 000 light-years long. The entire image is approximately 260 000 light-years across.

Credit: NASA, ESA and Andy Fabian (University of Cambridge, UK)

7 Hubble Ultra Deep Field is filled with galaxies

Galaxies, galaxies everywhere - as far as the Hubble Space Telescope can see. This view of nearly 10,000 galaxies is the deepest visible-light image of the cosmos. Called the Hubble Ultra Deep Field, this galaxy-studded view represents a "deep" core sample of the universe, cutting across billions of light-years.

The snapshot includes galaxies of various ages, sizes, shapes, and colours. The smallest, reddest galaxies, about 100, may be among the most distant known, existing when the universe was just 800 million years old. The nearest galaxies - the larger, brighter, well-defined spirals and ellipticals - thrived about 1 billion years ago, when the cosmos was 13 billion years old.

In vibrant contrast to the rich harvest of classic spiral and elliptical galaxies, there is a zoo of oddball galaxies littering the field. Some look like toothpicks; others like links on a bracelet. A few appear to be interacting. These oddball galaxies chronicle a period when the universe was younger and more chaotic.

In ground-based photographs, the patch of sky in which the galaxies reside (just one-tenth the diameter of the full Moon) is largely empty. Located in the constellation Fornax, the region is so empty that only a handful of stars within the Milky Way galaxy can be seen in the image.

The image required 800 exposures taken over the course of 400 Hubble orbits around Earth. The total amount of exposure time was 11.3 days, taken between Sept. 24, 2003 and Jan. 16, 2004.

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

"There are so many, but I have two favorite images:

"1) The Pillars of Creation [#82] is an iconic photograph taken by Hubble showing a glimpse of gas and dust regions veiling new star formation. This image was taken in 1995, long before my career in astronomy took off, while I was still only in middle school. There is something mysterious and beautiful about the process by which new stars are born.

"2) Fast forward a decade, into the era of Hubble Treasury programs, at which point 20-30% of Hubble's orbits were dedicated to large observing projects. The Hubble Ultra Deep Field revealed billions of years of cosmic growth for galaxies, including detections of the most distant known galaxies."

— Dr. Katherine E. Whitaker

NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

8 Hubble mosaic of the majestic Sombrero galaxy

Hubble has trained its razor-sharp eye on one of the universe's most stately and photogenic galaxies, the Sombrero galaxy, Messier 104 (M104). The galaxy's hallmark is a brilliant white, bulbous core encircled by the thick dust lanes comprising the spiral structure of the galaxy. As seen from Earth, the galaxy is tilted nearly edge-on. We view it from just six degrees north of its equatorial plane. This brilliant galaxy was named the Sombrero because of its resemblance to the broad rim and high-topped Mexican hat.

At a relatively bright magnitude of +8, M104 is just beyond the limit of naked-eye visibility and is easily seen through small telescopes. The Sombrero lies at the southern edge of the rich Virgo cluster of galaxies and is one of the most massive objects in that group, equivalent to 800 billion suns. The galaxy is 50,000 light-years across and is located 28 million light-years from Earth.

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

"Hubble changed everything: there was astronomy before Hubble, and astronomy after Hubble, and they are simply not the same. Hubble introduced a whole new era of high resolution imaging and precision measurements."

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland

New stars shed light on the past

This Hubble image depicts bright blue newly formed stars that are blowing a cavity in the centre of a fascinating star-forming region known as N90.

The high energy radiation blazing out from the hot young stars in N90 is eroding the outer portions of the nebula from the inside, as the diffuse outer reaches of the nebula prevent the energetic outflows from streaming away from the cluster directly. Because N90 is located far from the central body of the Small Magellanic Cloud, numerous background galaxies in this picture can be seen, delivering a grand backdrop for the stellar newcomers. The dust in the region gives these distant galaxies a reddish-brown tint.

Credit: NASA, ESA and the Hubble Heritage Team STScI/AURA)-ESA/ Hubble Collaboration

"I have fond memories of the Comet Shoemaker-Levy 9 impacts with Jupiter in 1994 [#52]. Many scientists, including myself, spent all week at the Space Telescope Science Institute analyzing the data and generating color images and maps of the impact scars in Jupiter's clouds. Because the telescope mirror had recently been corrected, the beautiful details visible in every image were amazing.

"Since then, I find that every new image is just as exciting and awe-inspiring. Perhaps one of my favorite images of Jupiter is from 2014 [#97]. We were using Hubble to study changes in the Great Red Spot, and when we began to process the images, we realized Ganymede's shadow was directly in the way!

"It was just incredibly poor timing, but it made for a spectacular and fun image."

— Dr. Amy A. Simon

Senior Scientist for Planetary Atmospheres
NASA Goddard Space Flight Center
Greenbelt, Maryland

10. Most detailed image of the Crab Nebula

This Hubble image - among the largest ever produced with the Earth-orbiting observatory - gives the most detailed view of the entire Crab Nebula ever. The Crab is among the most interesting and well studied objects in astronomy.

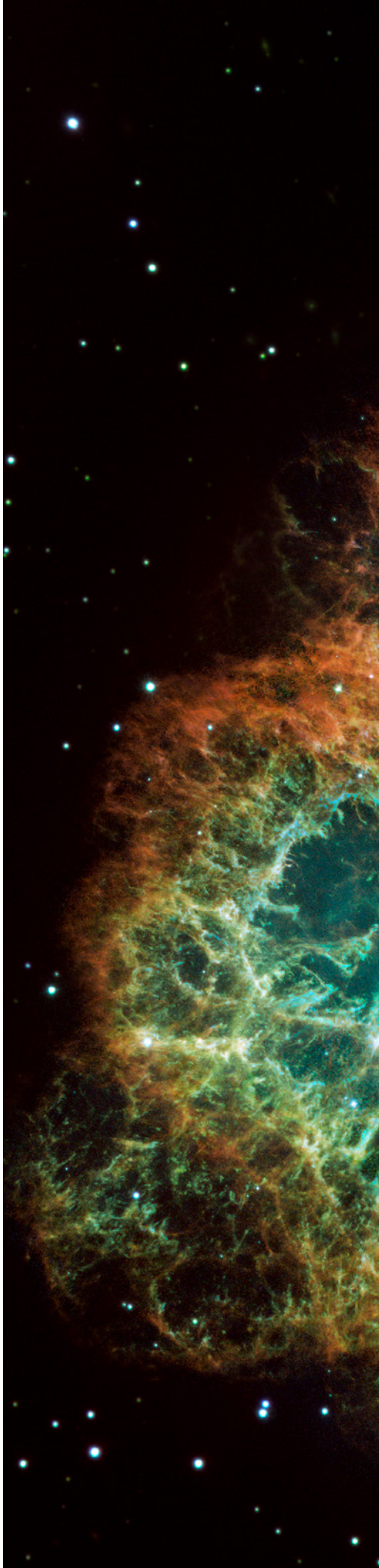
This image is the largest image ever taken with Hubble's WFPC2 camera. It was assembled from 24 individual exposures taken with the telescope and is the highest resolution image of the entire Crab Nebula ever made.

Credit: NASA, ESA and Allison Loll/Jeff Hester (Arizona State University)

"Hubble joined up a thousand years of astronomy, from the discovery of the supernova in 1054 that produced the Crab pulsar to the extraordinarily detailed images of its remnant taken with WFPC2 in 1999/2000."

— Dr. Boris Gänsicke

Professor in the Department of Physics
University of Warwick
Coventry, United Kingdom



11. Butterfly emerges from stellar demise in planetary nebula

This celestial object looks like a delicate butterfly. But it is far from serene. What resemble dainty butterfly wings are actually roiling cauldrons of gas heated to nearly 20 000 degrees Celsius. The gas is tearing across space at more than 950 000 kilometres per hour — fast enough to travel from Earth to the Moon in 24 minutes!

A dying star that was once about five times the mass of the Sun is at the centre of this fury. It has ejected its envelope of gases and is now unleashing a stream of ultraviolet radiation that is making the cast-off material glow. This object is an example of a planetary nebula, so-named because many of them have a round appearance resembling that of a planet when viewed through a small telescope.

The Wide Field Camera 3 (WFC3) aboard the NASA/ESA Hubble Space Telescope, snapped this image of the planetary nebula, catalogued as NGC 6302, but more popularly called the Bug Nebula or the Butterfly Nebula.

NGC 6302 lies within our Milky Way galaxy, roughly 3800 light-years away in the constellation of Scorpius. The glowing gas is the star's outer layers, expelled over about 2200 years. The "butterfly" stretches for more than two light-years, which is about half the distance from the Sun to the nearest star, Proxima Centauri.

The central star itself cannot be seen, because it is hidden within a doughnut-shaped ring of dust, which appears as a dark band pinching the nebula in the centre. The thick dust belt constricts the star's outflow, creating the classic "bipolar" or hourglass shape displayed by some planetary nebulae.

The star's surface temperature is estimated to be over 220 000 degrees Celsius, making it one of the hottest known stars in our galaxy. Spectroscopic observations made with ground-based telescopes show that the gas is roughly 20 000 degrees Celsius, which is unusually hot compared to a typical planetary nebula.

The WFC3 image reveals a complex history of ejections from the star. The star first evolved into a huge red giant, with a diameter of about 1000 times that of our Sun. It then lost its extended outer layers. Some of this gas was cast off from its equator at a relatively slow speed, perhaps as low as 32 000 kilometres per hour, creating the doughnut-shaped ring. Other gas was ejected perpendicular to the ring at higher speeds, producing the elongated "wings" of the butterfly-shaped structure. Later, as the central star heated up, a much faster stellar wind, a stream of charged particles travelling at more than 3.2 million kilometres per hour, ploughed through the existing wing-shaped structure, further modifying its shape.

The nebula's reddish outer edges are largely due to light emitted by nitrogen, which marks the coolest gas visible in the picture. WFC3 is equipped with a wide variety of filters that isolate light emitted by various chemical elements, allowing astronomers to infer properties of the nebular gas, such as its temperature, density and composition.

The white-coloured regions are areas where light is emitted by sulphur. These are regions where fast-moving gas overtakes and collides with slow-moving gas that left the star at an earlier time, producing shock waves in the gas (the bright white edges on the sides facing the central star). The white blob with the crisp edge at upper right is an example of one of those shock waves.

NGC 6302 was imaged on 27 July 2009 with Hubble's WFC3 in ultraviolet and visible light. Filters that isolate emissions from oxygen, helium, hydrogen, nitrogen and sulphur from the planetary nebula were used to create this composite image.

Credit: NASA, ESA and the Hubble SM4 ERO Team

12. Hubble's sharpest view of the Orion Nebula

This dramatic image offers a peek inside a cavern of roiling dust and gas where thousands of stars are forming. The image, taken by the Advanced Camera for Surveys (ACS) aboard the Hubble Space Telescope, represents the sharpest view ever taken of this region, called the Orion Nebula. More than 3,000 stars of various sizes appear in this image. Some of them have never been seen in visible light. These stars reside in a dramatic dust-and-gas landscape of plateaus, mountains, and valleys that are reminiscent of the Grand Canyon.

The Orion Nebula is a picture book of star formation, from the massive, young stars that are shaping the nebula to the pillars of dense gas that may be the homes of budding stars. The bright central region is the home of the four heftiest stars in the nebula. The stars are called the Trapezium because they are arranged in a trapezoid pattern. Ultraviolet light unleashed by these stars is carving a cavity in the nebula and disrupting the growth of hundreds of smaller stars. Located near the Trapezium stars are stars still young enough to have disks of material encircling them. These disks are called protoplanetary disks or "proplyds" and are too small to see clearly in this image. The disks are the building blocks of solar systems.

The bright glow at upper left is from M43, a small region being shaped by a massive, young star's ultraviolet light. Astronomers call the region a miniature Orion Nebula because only one star is sculpting the landscape. The Orion Nebula has four such stars. Next to M43 are dense, dark pillars of dust and gas that point toward the Trapezium. These pillars are resisting erosion from the Trapezium's intense ultraviolet light. The glowing region on the right reveals arcs and bubbles formed when stellar winds - streams of charged particles ejected from the Trapezium stars - collide with material.

The faint red stars near the bottom are the myriad brown dwarfs that Hubble spied for the first time in the nebula in visible light. Sometimes called "failed stars," brown dwarfs are cool objects that are too small to be ordinary stars because they cannot sustain nuclear fusion in their cores the way our Sun does. The dark red column, below, left, shows an illuminated edge of the cavity wall.

The Orion Nebula is 1,500 light-years away, the nearest star-forming region to Earth. Astronomers used 520 Hubble images, taken in five colours, to make this picture. They also added ground-based photos to fill out the nebula. The ACS mosaic covers approximately the apparent angular size of the full moon.

The Orion observations were taken between 2004 and 2005.

Credit: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team

13 Young stars sculpt gas with powerful outflows

This Hubble Space Telescope view shows one of the most dynamic and intricately detailed star-forming regions in space, located 210,000 light-years away in the Small Magellanic Cloud (SMC), a satellite galaxy of our Milky Way. At the centre of the region is a brilliant star cluster called NGC 346. A dramatic structure of arched, ragged filaments with a distinct ridge surrounds the cluster.

A torrent of radiation from the hot stars in the cluster NGC 346, at the centre of this Hubble image, eats into denser areas around it, creating a fantasy sculpture of dust and gas. The dark, intricately beaded edge of the ridge, seen in silhouette, is particularly dramatic. It contains several small dust globules that point back towards the central cluster, like windsocks caught in a gale.

Credit: NASA, ESA and A. Nota (ESA/STScI, STScI/AURA)

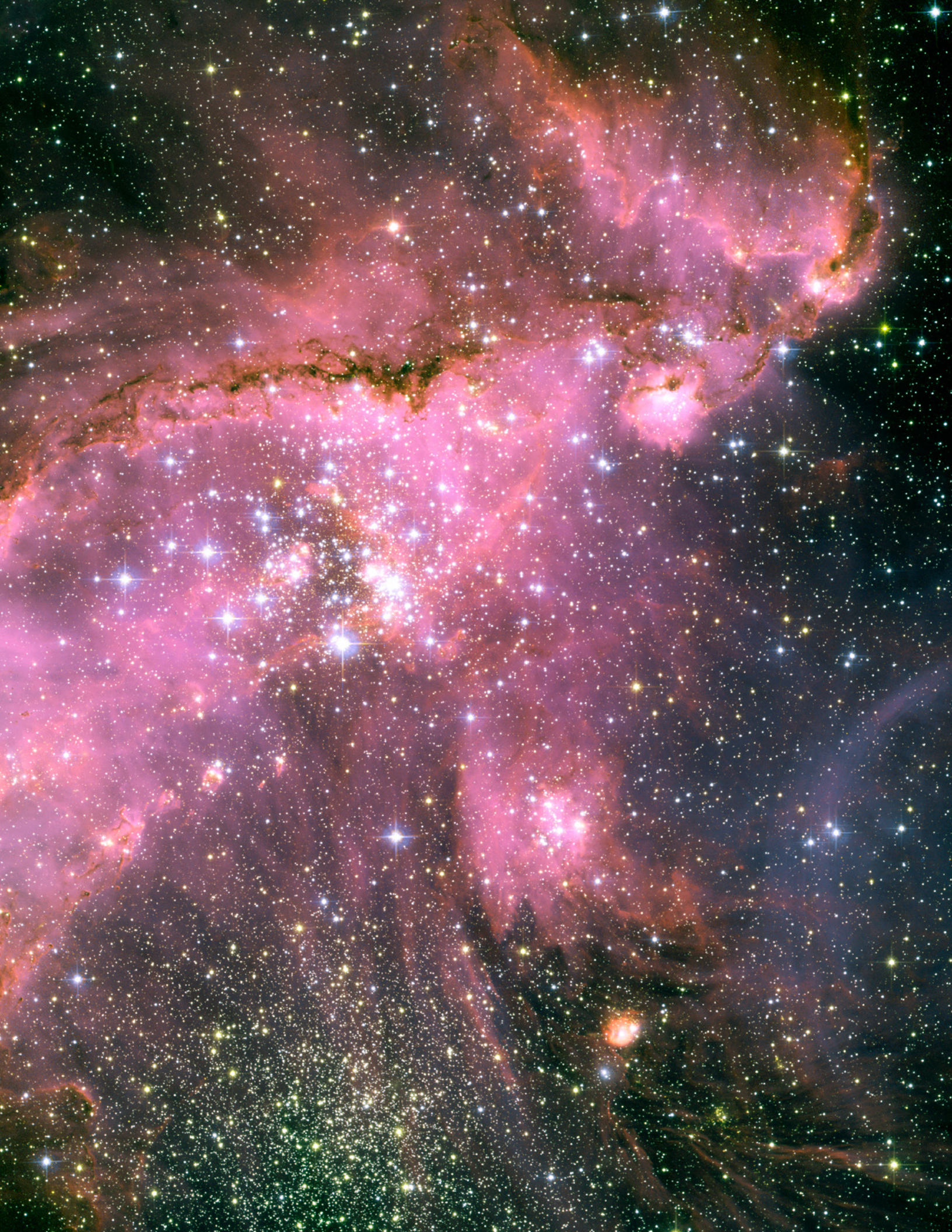
"After my PhD I spent three years at the Space Telescope Science Institute which is responsible for all the science operations with Hubble. This was a very exciting time. Especially during a certain week in the year, the week right before the proposal deadline, when all astronomers write what amazing science they would like to do with Hubble. In Baltimore, where nearly everyone uses Hubble, this week is crazy. Getting time on Hubble is very hard. Only 1 out of every 8 proposals gets time. And it takes a lot of effort to write a proposal.

"The weeks before, the Institute seems to be buzzing. People are excited to discuss wild ideas, brainstorm with each other how the instruments can be used to get the most out of it. For many it is a very stressful period, where most people barely get any sleep. But the intensity and passion people have for their work is very hard to describe and it really struck me.

"One of the better memories is of the colleague who would order many pizzas to support everyone who was still working on improving their proposals. If you realize how hard it is to get time and how competitive it is, it is very special to feel that supportive atmosphere in the Institute. People just want to amazing science with Hubble. That week they seem to give everything for it."

— Dr. Selma E. de Mink

Assistant Professor
University of Amsterdam
Netherlands



14. Out of this whirl: Whirlpool galaxy (M51) and companion galaxy

The graceful, winding arms of the majestic spiral galaxy M51 (NGC 5194) appear like a grand spiral staircase sweeping through space. They are actually long lanes of stars and gas laced with dust.

This sharpest-ever image, taken in January 2005 with the Advanced Camera for Surveys aboard the Hubble Space Telescope, illustrates a spiral galaxy's grand design, from its curving spiral arms, where young stars reside, to its yellowish central core, a home of older stars. The galaxy is nicknamed the Whirlpool because of its swirling structure.

The Whirlpool's most striking feature is its two curving arms, a hallmark of so-called grand-design spiral galaxies. Many spiral galaxies possess numerous, loosely shaped arms that make their spiral structure less pronounced. These arms serve an important purpose in spiral galaxies. They are star-formation factories, compressing hydrogen gas and creating clusters of new stars. In the Whirlpool, the assembly line begins with the dark clouds of gas on the inner edge, then moves to bright pink star-forming regions, and ends with the brilliant blue star clusters along the outer edge.

The Whirlpool is one of astronomy's galactic darlings. Located approximately 25 million light-years away in the constellation Canes Venatici (the Hunting Dogs), the Whirlpool's beautiful face-on view and closeness to Earth allow astronomers to study a classic spiral galaxy's structure and star-forming processes.

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

15. Stellar spire in the Eagle Nebula

Appearing like a winged fairy-tale creature poised on a pedestal, this object is actually a billowing tower of cold gas and dust rising from a stellar nursery called the Eagle Nebula. The soaring tower is 9.5 light-years or about 90 trillion kilometres high, about twice the distance from our Sun to the next nearest star.

Stars in the Eagle Nebula are born in clouds of cold hydrogen gas that reside in chaotic neighbourhoods, where energy from young stars sculpts fantasy-like landscapes in the gas. The tower may be a giant incubator for those newborn stars. A torrent of ultraviolet light from a band of massive, hot, young stars [off the top of the image] is eroding the pillar.

The starlight also is responsible for illuminating the tower's rough surface. Ghostly streamers of gas can be seen boiling off this surface, creating the haze around the structure and highlighting its three-dimensional shape. The column is silhouetted against the background glow of more distant gas.

Inside the gaseous tower, stars may be forming. Some of those stars may have been created by dense gas collapsing under gravity. Other stars may be forming due to pressure from gas that has been heated by the neighbouring hot stars.

The bumps and fingers of material in the centre of the tower are examples of these stellar birthing areas. These regions may look small but they are roughly the size of our solar system.

The dominant colours in the image were produced by gas energized by the star cluster's powerful ultraviolet light. The blue colour at the top is from glowing oxygen. The red color in the lower region is from glowing hydrogen. The Eagle Nebula image was taken in November 2004 with the ACS aboard Hubble.

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

16. Cosmic dust bunnies

Like dust bunnies that lurk in corners and under beds, surprisingly complex loops and blobs of cosmic dust lie hidden in the giant elliptical galaxy NGC 1316. This image made from data obtained with Hubble reveals the dust lanes and star clusters of this giant galaxy that give evidence that it was formed from a past merger of two gas-rich galaxies.

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

"The Hubble Space Telescope has revolutionized astronomy in many ways. As beautifully illustrated by the Top 100 gallery, it has produced thousands of stunning pictures giving us a sharper view to the universe than ever before, and allowing for unprecedented insights into the cosmos.

"In every area of astronomy HST has made discovery that were completely unanticipated during its planning stages. This is a true sign of a revolutionary observatory. For example, in one of my areas of interest, gravitational lensing, HST has been transformative. With its superb angular resolution it has allowed astronomers to transform what was thought to be a mere curiosity with no chances of ever been observed (including by Einstein's himself!) into a workhorse for cosmology.

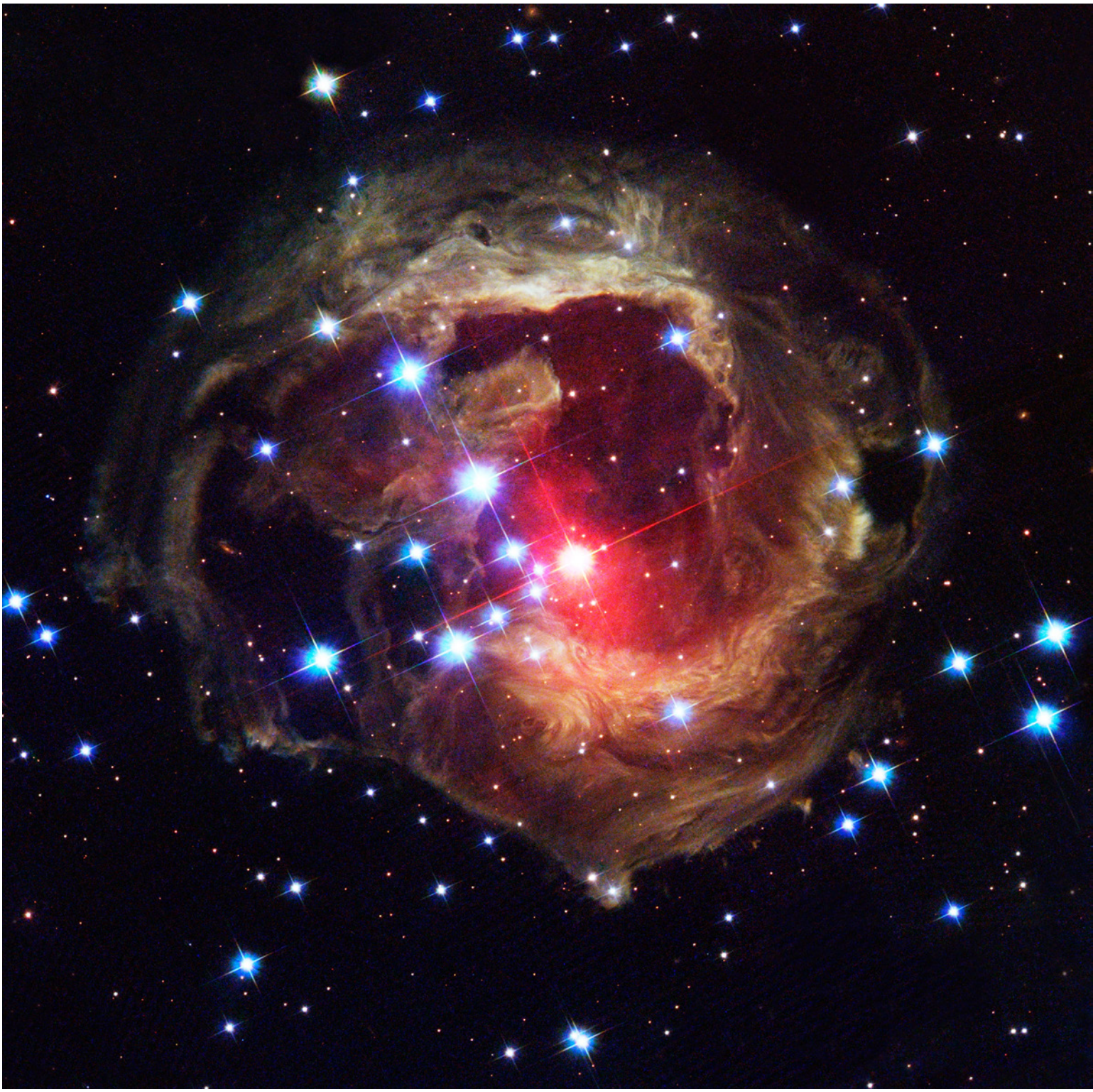
"With Hubble and gravitational lensing we have learned about the first galaxies ever to form in the universe, and we have learned about the fundamental nature of dark matter and dark energy, just to name a couple of topics. Recent examples of gravitational lensing work that I have been involved in are the discovery of the multiply imaged supernova 'Refsdal' [see inside back cover for story] and of the first double Einstein Ring.*

"On a more personal level, HST has transformed my life as well. It was after an undergraduate summer research experience at the Space Telescope Science Institute that I decided to go to graduate school in physics and pursue a career as an astrophysicist."

– Tommaso Treu

Professor
University of California, Los Angeles

** http://hubblesite.org/newscenter/archive/releases/2008/04/*



17. Light continues to echo three years after stellar outburst

This Hubble image of the star V838 Monocerotis (V838 Mon) reveals dramatic changes in the illumination of surrounding dusty cloud structures. The effect, called a light echo, has been unveiling never-before-seen dust patterns ever since the star suddenly brightened for several weeks in early 2002.

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

"With a superior resolving power to most other telescopes and the unobscured view of the universe from above our atmosphere, Hubble takes truly beautiful, unique images of the cosmos."

— Dr. Katherine E. Whitaker

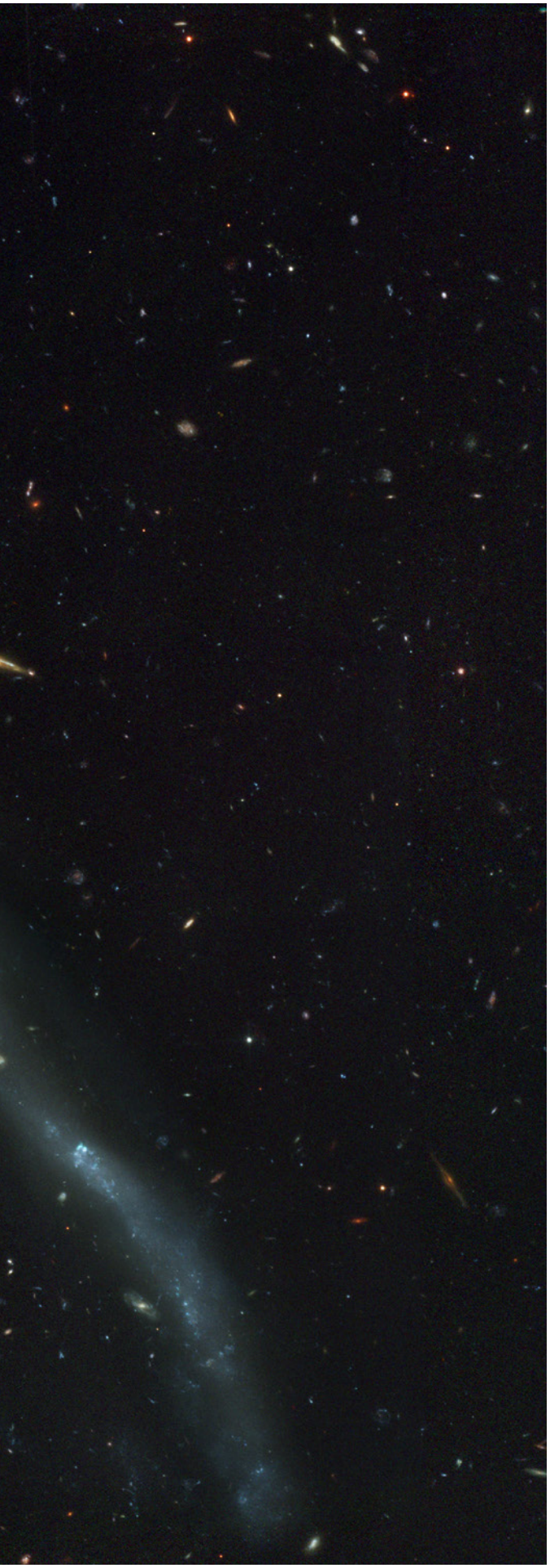
NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

18. Beautiful barred spiral galaxy NGC 1300

One of the largest Hubble Space Telescope images ever made of a complete galaxy was unveiled at the American Astronomical Society meeting in San Diego, Calif.

The Hubble telescope captured a display of starlight, glowing gas, and silhouetted dark clouds of interstellar dust in this 4-foot-by-8-foot image of the barred spiral galaxy NGC 1300. NGC 1300 is considered to be prototypical of barred spiral galaxies. Barred spirals differ from normal spiral galaxies in that the arms of the galaxy do not spiral all the way into the center, but are connected to the two ends of a straight bar of stars containing the nucleus at its center.

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



19. A runaway galaxy

Against a stunning backdrop of thousands of galaxies, this odd-looking galaxy with the long streamer of stars appears to be racing through space, like a runaway pinwheel firework.

Galaxy UGC 10214's distorted shape was caused by a small interloper, a very blue, compact, galaxy visible in the upper left corner of the more massive Tadpole. The Tadpole resides about 420 million light-years away in the constellation Draco.

Numerous young blue stars and star clusters, spawned by the galaxy collision, are seen in the spiral arms, as well as in the long 'tidal' tail of stars. Each of these clusters represents the formation of up to about a million stars. Two prominent clumps of young bright blue stars are visible in the tidal tale and separated by a gap. These clumps of stars will likely become dwarf galaxies that orbit in the Tadpole's halo.

Behind the galactic carnage and torrent of star birth is another compelling picture: a 'wallpaper pattern' of about 3000 faint galaxies. The camera's vision is so sharp that astronomers can identify distant colliding galaxies, the 'building blocks' of galaxies, an exquisite 'Whitman's Sampler' of normal galaxies, and presumably extremely faraway galaxies.

Credit: NASA, Holland Ford (JHU), the ACS Science Team and ESA

20. A deep look at two merging galaxies

The Advanced Camera for Surveys (ACS) aboard Hubble captured a spectacular pair of galaxies engaged in a celestial dance of cat and mouse or, in this case, mouse and mouse.

Located 300 million light-years away in the constellation Coma Berenices, the colliding galaxies have been nicknamed "The Mice" because of the long tails of stars and gas emanating from each galaxy. Otherwise known as NGC 4676, the pair will eventually merge into a single giant galaxy.

Credit: NASA, Holland Ford (JHU), the ACS Science Team and ESA

21. Ghostly star-forming pillar of gas and dust

Resembling a nightmarish beast rearing its head from a crimson sea, this celestial object is actually just a pillar of gas and dust. Called the Cone Nebula (in NGC 2264) this monstrous pillar resides in a turbulent star-forming region. This picture shows the upper 2.5 light-years of the Cone.

Radiation from hot, young stars (located beyond the top of the image) has slowly eroded the nebula over millions of years. Ultraviolet light heats the edges of the dark cloud, releasing gas into the relatively empty region of surrounding space. There, additional ultraviolet radiation causes the hydrogen gas to glow, which produces the red halo of light seen around the pillar.

Credit: NASA, Holland Ford (JHU), the ACS Science Team and ESA

22. Red Spider Nebula

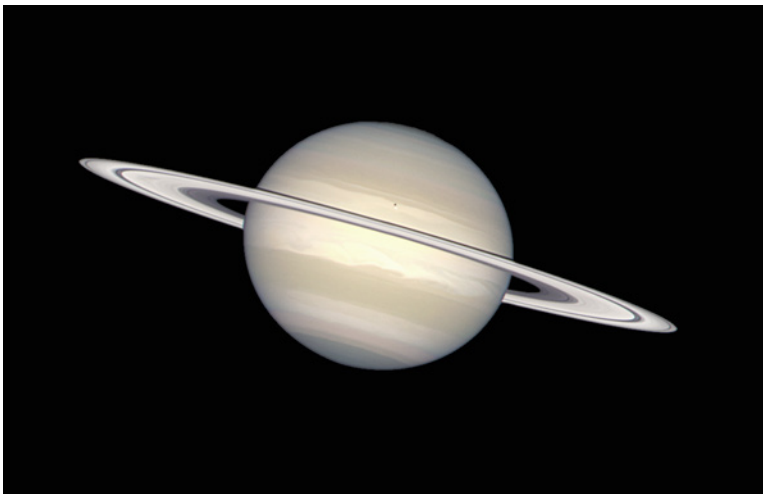
Huge waves are sculpted in this two-lobed nebula some 3000 light-years away in the constellation of Sagittarius. This warm planetary nebula harbours one of the hottest stars known and its powerful stellar winds generate waves 100 billion kilometres high. The waves are caused by supersonic shocks, formed when the local gas is compressed and heated in front of the rapidly expanding lobes. The atoms caught in the shock emit the spectacular radiation seen in this image.

Credit: ESA & Garrelt Mellema (Leiden University, the Netherlands)

23. Light and shadow in the Carina Nebula

Previously unseen details of a mysterious, complex structure within the Carina Nebula (NGC 3372) are revealed by this image of the 'Keyhole Nebula.'. The picture is a montage assembled from four different April 1999 telescope pointings with Hubble's Wide Field Planetary Camera 2, which used six different colour filters. The picture is dominated by a large, approximately circular feature, which is part of the Keyhole Nebula, named in the 19th century by Sir John Herschel. This region, about 8000 light-years from Earth, is located adjacent to the famous explosive variable star Eta Carinae, which lies just outside the field of view toward the upper right. The Carina Nebula also contains several other stars that are among the hottest and most massive known, each about 10 times as hot, and 100 times as massive, as our Sun.

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



24. Saturn in natural colours

The ring swirling around Saturn consists of chunks of ice and dust. Saturn itself is made of ammonia ice and methane gas. The little dark spot on Saturn is the shadow from Saturn's moon Enceladus.

Hubble has provided images of Saturn in many colors, from black-and-white, to orange, to blue, green, and red. But in this picture, image processing specialists have worked to provide a crisp, extremely accurate view of Saturn, which highlights the planet's pastel colors. Bands of subtle colour - yellows, browns, grays - distinguish differences in the clouds over Saturn, the second largest planet in the solar system.

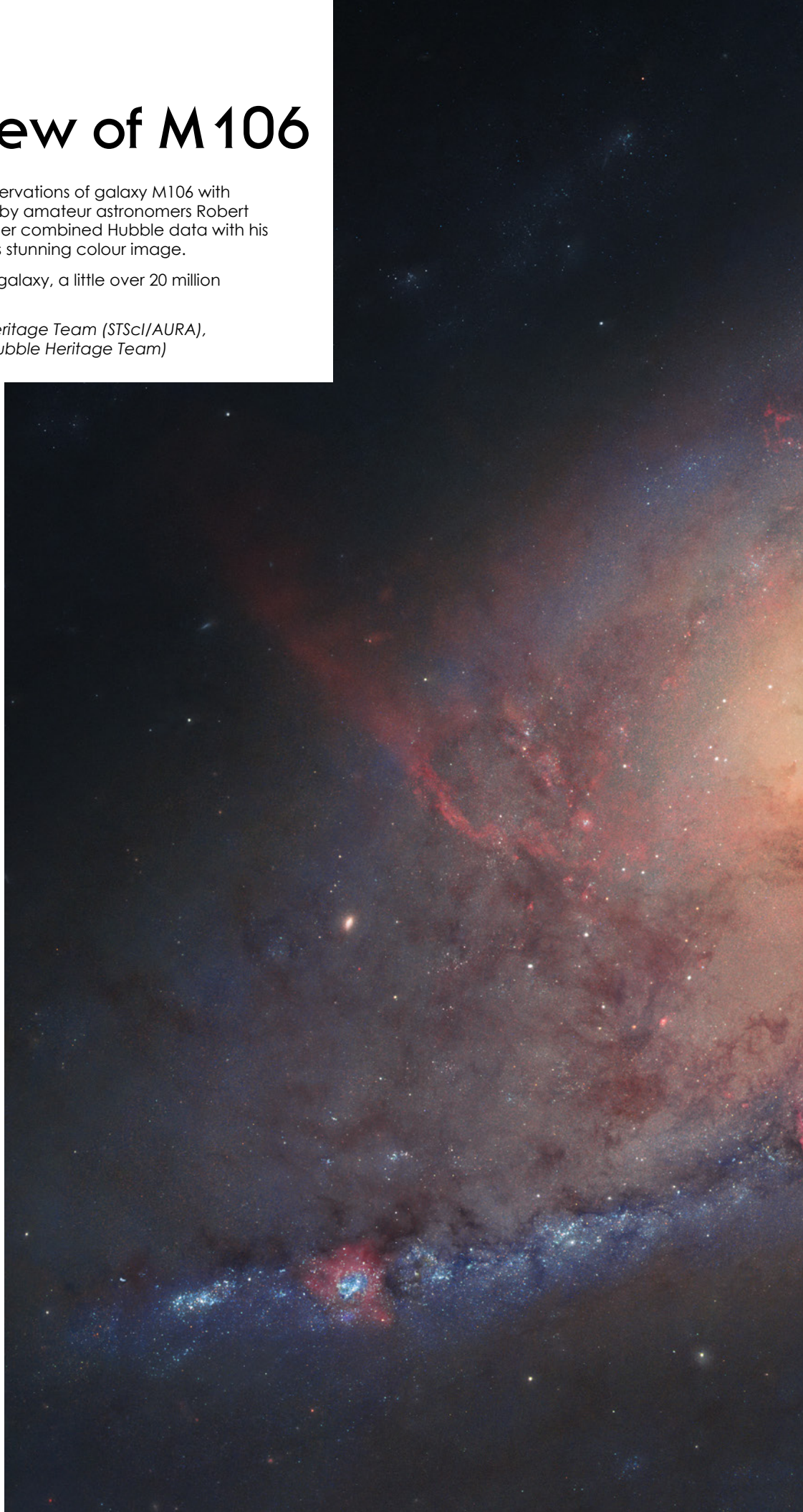
Credit: Hubble Heritage Team (AURA/STScI/NASA/ESA)

25. Stunning view of M106

This image combines Hubble observations of galaxy M106 with additional information captured by amateur astronomers Robert Gendler and Jay GaBany. Gendler combined Hubble data with his own observations to produce this stunning colour image.

M106 is a relatively nearby spiral galaxy, a little over 20 million light-years away.

Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), and R. Gendler (for the Hubble Heritage Team)



26. Hubble snaps close-up of the Tarantula Nebula

Hubble has taken this stunning close-up shot of part of the Tarantula Nebula. This star-forming region of ionised hydrogen gas is in the Large Magellanic Cloud, a small galaxy which neighbours the Milky Way. It is home to many extreme conditions including supernova remnants and the heaviest star ever found. The Tarantula Nebula is the most luminous nebula of its type in the local Universe.

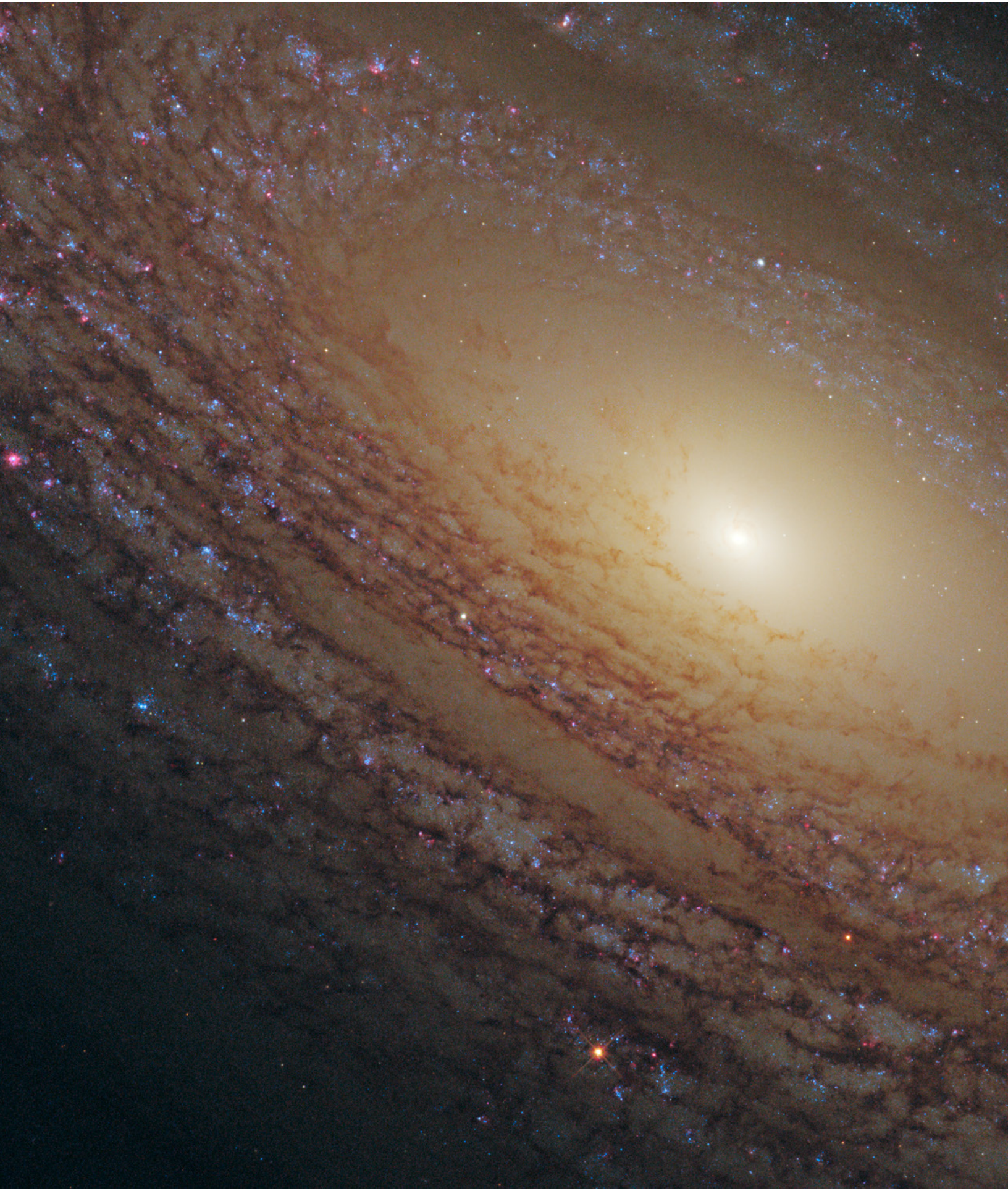
Credit: NASA, ESA

"This region is called the Tarantula Nebula (cause the dust filaments on an image with a simple telescope have the appearance of the arms of a spider). At the very heart of the nebula sits a star cluster that is hosting many massive stars, several of them, as we now know are a few hundred times the mass of our Sun, much larger than was widely assumed. At the moment we are using one of the spectrographs (an instrument that unravels the light into different wavelengths to truly reveal the scientific data imprinted in the light) to study the properties of these extreme beasts in the center of the nebula in a program lead by P. Crowther. We would like to know if they are single stars, or maybe they are binaries.

"We want to know if they rotate like normal stars do. We want to know what chemical elements we see at their surface. We want to know how they radiate. We want to know about the strong winds they blow of their surface. And all these questions together will teach us how these massive stars live their lives, how they play their role as cosmic engines. How did such stars over the history of the cosmos change the pristine Universe left after the big bang into the modern universe in which we live today? I am fascinated and maybe a little obsessed to understand these massive stars, because they are key to understanding an important piece in the big question about our cosmic origin: how did we get here?"

— Dr. Selma E. de Mink

Assistant Professor
University of Amsterdam
Netherlands



27. Flocculent spiral NGC 2841

Star formation is one of the most important processes in shaping the Universe; it plays a pivotal role in the evolution of galaxies and it is also in the earliest stages of star formation that planetary systems first appear.

Yet there is still much that astronomers don't understand, such as how do the properties of stellar nurseries vary according to the composition and density of gas present, and what triggers star formation in the first place? The driving force behind star formation is particularly unclear for a type of galaxy called a flocculent spiral, such as NGC 2841 shown here, which features short spiral arms rather than prominent and well-defined galactic limbs.

Credit: NASA, ESA and the Hubble Heritage (STScI/ AURA)-ESA/Hubble Collaboration

"Hubble has revolutionized our understanding of the structures of distant galaxies. By working with Hubble data, I have continued to be surprised by the new and unexpected discoveries that result."

— Dr. Katherine E. Whitaker

NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

29. Hubble captures view of 'Mystic Mountain'

This craggy fantasy mountaintop enshrouded by wispy clouds looks like a bizarre landscape from Tolkien's The Lord of the Rings. This Hubble image, which is even more dramatic than fiction, captures the chaotic activity atop a pillar of gas and dust, three light-years tall, which is being eaten away by the brilliant light from nearby bright stars. The pillar is also being assaulted from within, as infant stars buried inside it fire off jets of gas that can be seen streaming from towering peaks.

This turbulent cosmic pinnacle lies within a tempestuous stellar nursery called the Carina Nebula, located 7500 light-years away in the southern constellation of Carina. The image celebrates the 20th anniversary of Hubble's launch and deployment into an orbit around the Earth.

Scorching radiation and fast winds (streams of charged particles) from super-hot newborn stars in the nebula are shaping and compressing the pillar, causing new stars to form within it. Streamers of hot ionised gas can be seen flowing off the ridges of the structure, and wispy veils of gas and dust, illuminated by starlight, float around its towering peaks. The denser parts of the pillar are resisting being eroded by radiation.

Nestled inside this dense mountain are fledgling stars. Long streamers of gas can be seen shooting in opposite directions from the pedestal at the top of the image. Another pair of jets is visible at another peak near the centre of the image. These jets, (known as HH 901 and HH 902, respectively, are signposts for new star birth and are launched by swirling gas and dust discs around the young stars, which allow material to slowly accrete onto the stellar surfaces.

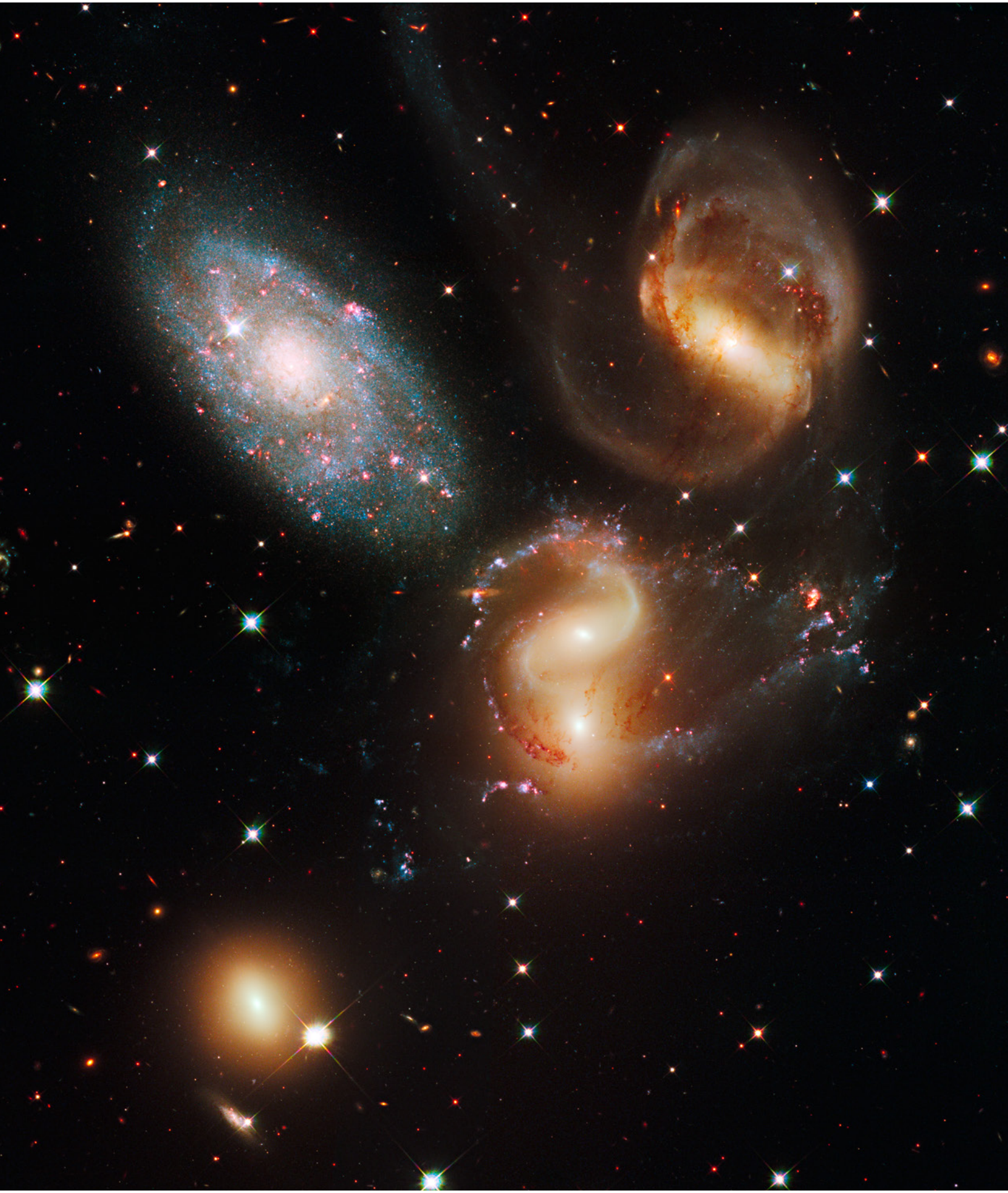
Hubble's Wide Field Camera 3 observed the pillar on 1-2 February 2010. The colours in this composite image correspond to the glow of oxygen (blue), hydrogen and nitrogen (green), and sulphur (red).

Credit: NASA, ESA, M. Livio and the Hubble 20th Anniversary Team (STScI)

"I'm part of a generation of astronomers that grew up surrounded by Hubble images, and I can safely say that they were a big part of the reason why I became an astronomer. Of course, having my college physics classes across the street from the Space Telescope Science Institute (ground zero for Hubble) didn't hurt, either."

— Dr. Heather Knutson

Assistant Professor of Planetary Science
California Institute of Technology
Pasadena, California



29. Galactic wreckage in Stephan's Quintet

A clash among members of a famous galaxy quintet reveals an assortment of stars across a wide colour range, from young, blue stars to aging, red stars.

This portrait of Stephan's Quintet, also known as the Hickson Compact Group 92, was taken by the new Wide Field Camera 3 (WFC3) aboard Hubble. Stephan's Quintet, as the name implies, is a group of five galaxies. The name, however, is a bit of a misnomer. Studies have shown that group member NGC 7320, at upper left, is actually a foreground galaxy that is about seven times closer to Earth than the rest of the group.

Three of the galaxies have distorted shapes, elongated spiral arms, and long, gaseous tidal tails containing myriad star clusters, proof of their close encounters. These interactions have sparked a frenzy of star birth in the central pair of galaxies. This drama is being played out against a rich backdrop of faraway galaxies.

The image, taken in visible and near-infrared light, showcases WFC3's broad wavelength range. The colours trace the ages of the stellar populations, showing that star birth occurred at different epochs, stretching over hundreds of millions of years. The camera's infrared vision also peers through curtains of dust to see groupings of stars that cannot be seen in visible light.

NGC 7319, at top right, is a barred spiral with distinct spiral arms that follow nearly 180 degrees back to the bar. The blue specks in the spiral arm at the top of NGC 7319 and the red dots just above and to the right of the core are clusters of many thousands of stars. Most of the Quintet is too far away even for Hubble to resolve individual stars.

Continuing clockwise, the next galaxy appears to have two cores, but it is actually two galaxies, NGC 7318A and NGC 7318B. Encircling the galaxies are young, bright blue star clusters and pinkish clouds of glowing hydrogen where infant stars are being born. These stars are less than 10 million years old and have not yet blown away their natal cloud. Far away from the galaxies, at right, is a patch of intergalactic space where many star clusters are forming.

NGC 7317, at bottom left, is a normal-looking elliptical galaxy that is less affected by the interactions.

Sharply contrasting with these galaxies is the dwarf galaxy NGC 7320 at upper left. Bursts of star formation are occurring in the galaxy's disc, as seen by the blue and pink dots. In this galaxy, Hubble can resolve individual stars, evidence that NGC 7320 is closer to Earth. NGC 7320 is 40 million light-years from Earth. The other members of the Quintet reside about 300 million light-years away in the constellation Pegasus.

Spied by Edouard M. Stephan in 1877, Stephan's Quintet is the first compact group ever discovered.

WFC3 observed the Quintet in July and August 2009. The composite image was made by using filters that isolate light from the blue, green and infrared portions of the spectrum, as well as emission from ionised hydrogen.

Credit: NASA, ESA and the Hubble SM4 ERO Team

"Without Hubble, our state of understanding of the Universe would have huge gaps where we'd have no real idea, especially in the ultraviolet region of the spectrum. In other areas of astronomy, we might be only 10 years behind where we are now."

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland

30. Barred spiral galaxy NGC 6217

This is the first image of a celestial object taken with the then newly repaired Advanced Camera for Surveys. The camera was restored to operation during the STS-125 Servicing Mission.

The barred spiral galaxy NGC 6217 was photographed on 13 June and 8 July 2009, as part of the initial testing and calibration of Hubble's ACS. The galaxy lies up to 90 million light-years away in the north circumpolar constellation Ursa Major.

Credit: NASA, ESA and the Hubble SM4 ERO Team

31. Backlit dust lanes in NGC 7049

The Hubble Space Telescope captured this image of NGC 7049 in the constellation of Indus, in the southern sky. A family of globular clusters appears as glittering spots dusted around the galaxy halo. Astronomers study the globular clusters in NGC 7049 to learn more about its formation and evolution. The dust lanes, which appear as a lacy web, are dramatically backlit by the millions of stars in the halo of NGC 7049.

Credit: NASA, ESA and W. Harris (McMaster University, Ontario, Canada)

32. Holiday cheer of galaxy M74

In this Hubble image of the galaxy M74 we can also see a smattering of bright pink regions decorating the spiral arms. These are huge, relatively short-lived, clouds of hydrogen gas which glow due to the strong radiation from hot, young stars embedded within them; glowing pink regions of ionized hydrogen (hydrogen that has lost its electrons). These regions of star formation show an excess of light at ultraviolet wavelengths and astronomers call them HII regions.

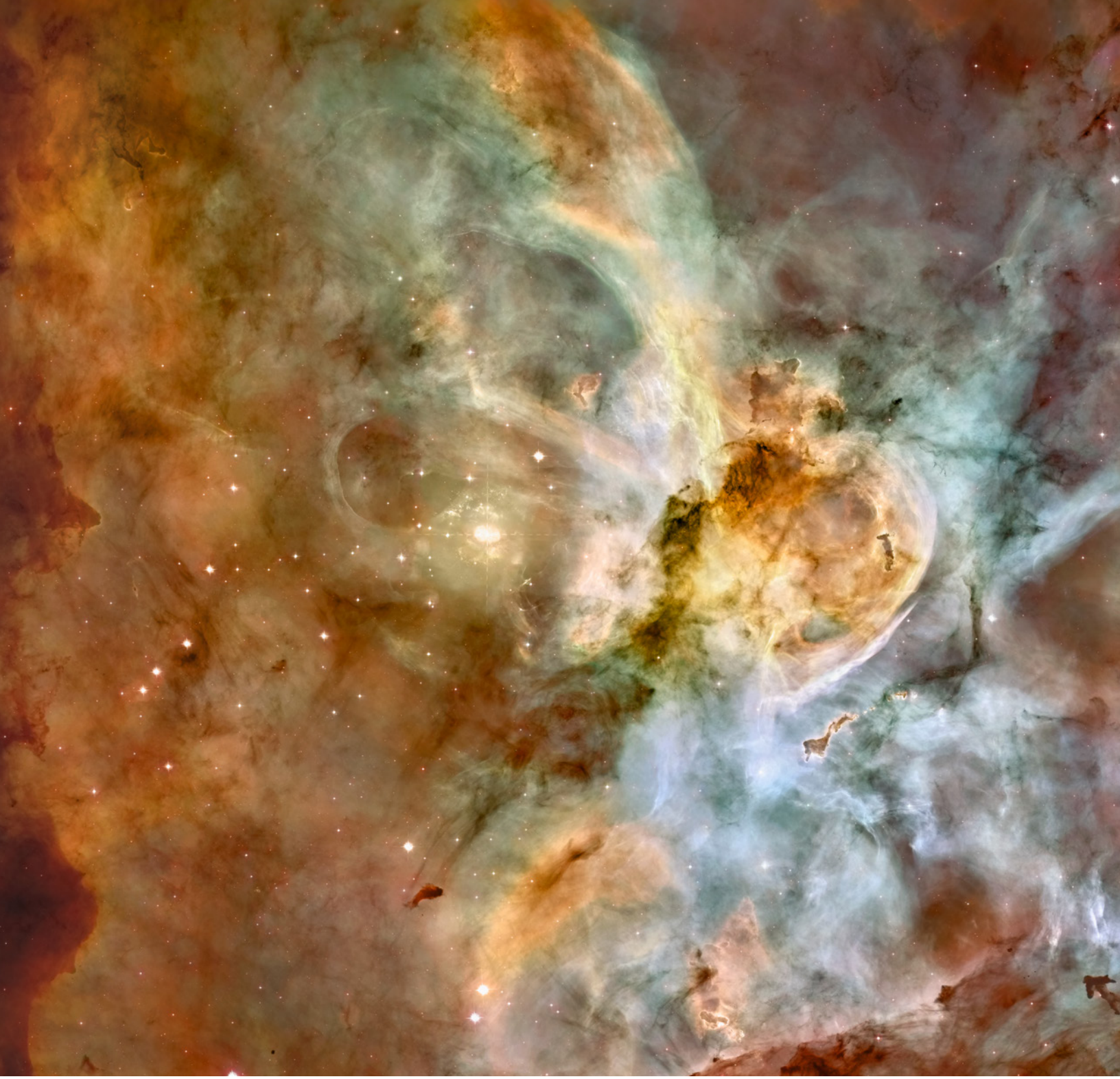
Credit: NASA, ESA, and The Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration

"By far my favorite image (and I know I'm biased here) is the Bullet Cluster image. I was directly involved with the research, and with a powerful combination of Hubble and Chandra we have shown that dark matter exist, and have directly measured its properties for the first time. Dark matter, mysterious stuff that makes up 25% of the universe turned out to be very anti social. Or in the words of Sean Caroll, 'Most of the Universe can't even be bothered to interact with you.' And that just means that it is absolutely fascinating."*

— Marusa Bradac

Associate Professor
University of California Davis

** http://hubblesite.org/newscenter/archive/releases/2008/32/*

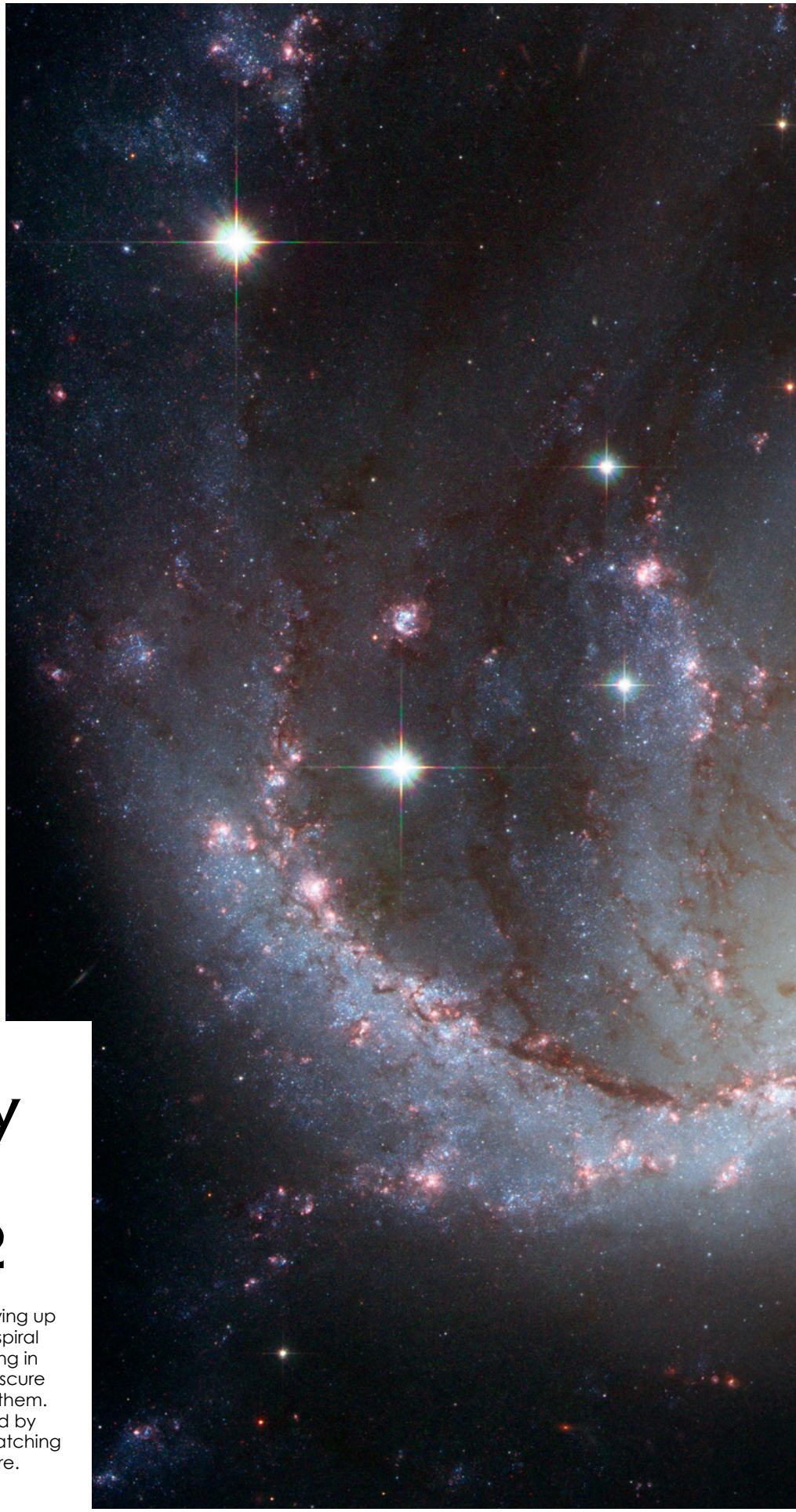


33. Star birth in the extreme

Hubble's view of the Carina Nebula shows star birth in a new level of detail. The fantasy-like landscape of the nebula is sculpted by the action of outflowing winds and scorching ultraviolet radiation from the monster stars that inhabit this inferno. In the process, these stars are shredding the surrounding material that is the last vestige of the giant cloud from which the stars were born. The immense nebula is an estimated 7,500 light-years away in the southern constellation Carina the Keel (of the old southern constellation Argo Navis, the ship of Jason and the Argonauts, from Greek mythology).

This image is a mosaic of the Carina Nebula assembled from 48 frames taken with Hubble's ACS. The images were taken in the light of ionized hydrogen. Colour information was added with data taken at the Cerro Tololo Inter-American Observatory in Chile. Red corresponds to sulfur, green to hydrogen, and blue to oxygen emission.

Credit: NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA)



34. Stellar nursery in the arms of NGC 1672

The barred spiral galaxy NGC 1672, showing up clusters of hot young blue stars along its spiral arms, and clouds of hydrogen gas glowing in red. Delicate curtains of dust partially obscure and redden the light of the stars behind them. NGC 1672's symmetric look is emphasised by the four principal arms, edged by eye-catching dust lanes that extend out from the centre.

Credit: NASA, ESA

35. Edge-on view of NGC 5866

This is a unique view of the disk galaxy NGC 5866 tilted nearly edge-on to our line-of-sight.

Hubble's sharp vision reveals a crisp dust lane dividing the galaxy into two halves. The image highlights the galaxy's structure: a subtle, reddish bulge surrounding a bright nucleus, a blue disk of stars running parallel to the dust lane, and a transparent outer halo.

Some faint, wispy trails of dust can be seen meandering away from the disk of the galaxy out into the bulge and inner halo of the galaxy. The outer halo is dotted with numerous gravitationally bound clusters of nearly a million stars each, known as globular clusters. Background galaxies that are millions to billions of light-years farther away than NGC 5866 are also seen through the halo.

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

*"Our favorite image is one not even in our own field: it's the picture of Omega Centauri, the largest globular cluster in the Milky Way.**

"The color composite early release image that was obtained with WFC3 shortly after it was installed in 2009 was amazing: the stars are so densely packed that in ground-based images, the stars are all blended together. But in the WFC3 image, you can see black space between the stars, you can see all the way through the cluster.

"In the color composite, you can easily pick out the relatively rare red giants and blue horizontal branch stars. It's simply stunning."

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland

** http://hubblesite.org/newscenter/archive/releases/2009/25/image/d/*

36. Magnificent starburst galaxy Messier 82

This mosaic image of the magnificent starburst galaxy, Messier 82 (M82) is the sharpest wide-angle view ever obtained of M82. It is a galaxy remarkable for its webs of shredded clouds and flame-like plumes of glowing hydrogen blasting out from its central regions where young stars are being born 10 times faster than they are inside in our Milky Way Galaxy.

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

"The beauty of Hubble is that we continue to make new, unforeseen discoveries. So with every new cycle of observations we are afforded, my answer to that question [of what should be Hubble's last image target] will likely change."

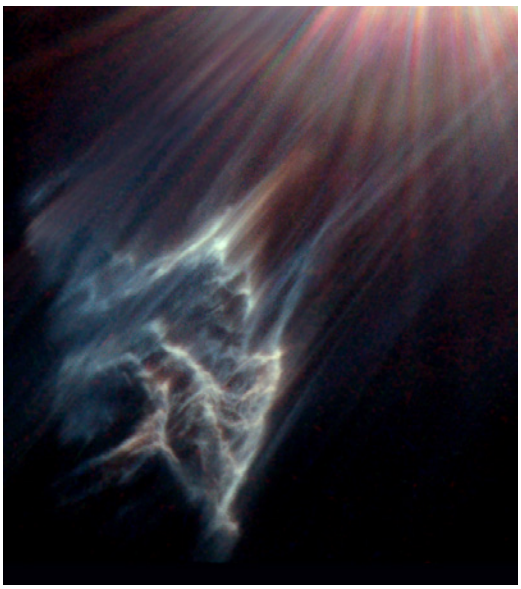
— Dr. Katherine E. Whitaker

NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

37. Pinwheel galaxy

This image reveals the gigantic Pinwheel galaxy, one of the best known examples of "grand design spirals", and its supergiant star-forming regions in unprecedented detail. The image is the largest and most detailed photo of a spiral galaxy ever taken with Hubble.

Credit: European Space Agency & NASA



38. Ghostly reflections in the Pleiades

This image shows a dark interstellar cloud ravaged by the passage of Merope, one of the brightest stars in the Pleiades star cluster. Just as a torch beam bounces off the wall of a cave, the star is reflecting light from the surface of pitch-black clouds of cold gas laced with dust. As the nebula approaches Merope, the strong starlight shining on the dust decelerates the dust particles. The nebula is drifting through the cluster at a relative speed of roughly 11 kilometres per second.

The Hubble Space Telescope has caught the eerie, wispy tendrils of a dark interstellar cloud being destroyed by the passage of one of the brightest stars in the Pleiades star cluster. Like a flashlight beam shining off the wall of a cave, the star is reflecting light off the surface of pitch black clouds of cold gas laced with dust. These are called reflection nebulae.

Credit: NASA/ESA and The Hubble Heritage Team STScI/AURA), George Herbig and Theodore Simon (University of Hawaii)

39. Spirograph Nebula

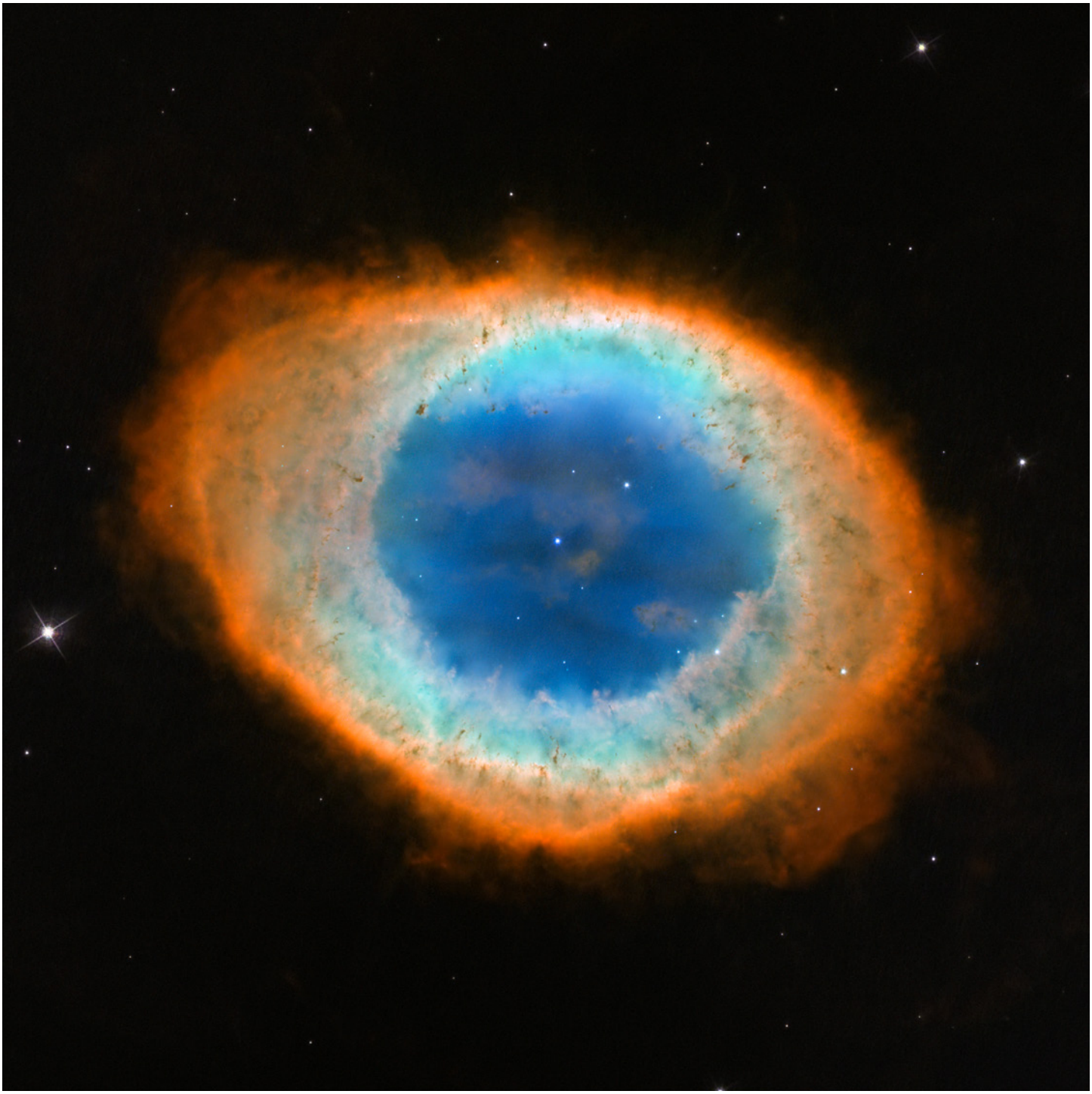
Glowing like a multi-faceted jewel, the planetary nebula IC 418 lies about 2000 light-years from Earth in the constellation Lepus. In this picture, the Hubble telescope reveals some remarkable textures weaving through the nebula. Their origin, however, is still uncertain.

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

40. Grazing encounter between two spiral galaxies

In the direction of the constellation Canis Major, two spiral galaxies pass by each other like majestic ships in the night. The near-collision has been caught in images taken by the NASA/ESA Hubble Space Telescope and its Wide Field Planetary Camera 2.

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



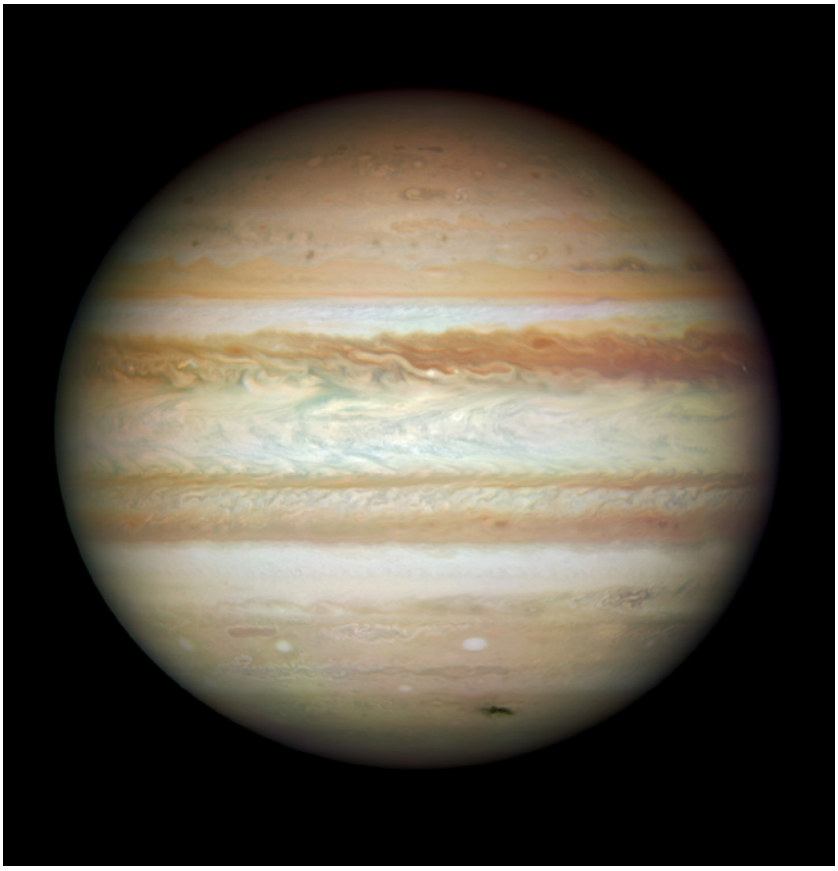
41. Dramatic Ring Nebula

This image shows the dramatic shape and colour of the Ring Nebula, otherwise known as Messier 57.

From Earth's perspective, the nebula looks like a simple elliptical shape with a shaggy boundary. However, new observations combining existing ground-based data with new Hubble Space Telescope data show that the nebula is shaped like a distorted doughnut. This doughnut has a rugby-ball-shaped region of lower-density material slotted into in its central "gap", stretching towards and away from us.

Credit: NASA, ESA, and C. Robert O'Dell (Vanderbilt University)

42. Collision bruises Jupiter

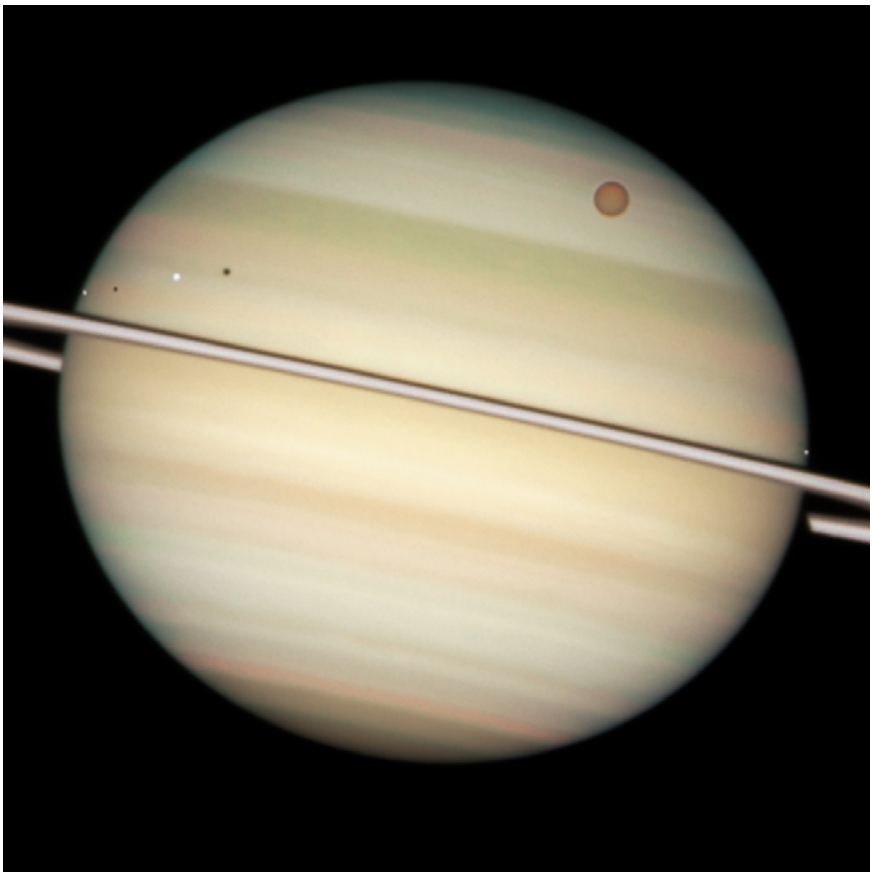


This is the first full-disc, natural-colour image of Jupiter made with Hubble's Wide Field Camera 3 (WFC3). It is the sharpest visible-light picture of Jupiter since the New Horizons spacecraft flew by in 2007. Each pixel in this high-resolution image spans about 119 kilometres in Jupiter's atmosphere. Jupiter was more than 600 million kilometres from Earth when the images were taken.

The dark smudge at bottom right is debris from a comet or asteroid that plunged into Jupiter's atmosphere and disintegrated.

In addition to the fresh impact, the image reveals a spectacular variety of shapes in the swirling atmosphere of Jupiter. The planet is wrapped in bands of yellow, brown and white clouds. These bands are produced by the atmosphere flowing in different directions at various places. When these opposing flows interact, turbulence appears.

Credit: NASA, ESA, Michael Wong (Space Telescope Science Institute, Baltimore, MD), H. B. Hammel (Space Science Institute, Boulder, CO) and the Jupiter Impact Team



43. Quadruple moon transit

This close-up view of Saturn's disc captures the transit of several moons across the face of the gas giant planet. The giant orange moon Titan — larger than the planet Mercury — can be seen at upper right. The white icy moons that are much closer to Saturn, hence much closer to the ring plane in this view, are, from left to right: Enceladus, Dione, and Mimas. The dark band running across the face of the planet slightly above the rings is the shadow of the rings cast on the planet. This picture was taken on 24 February 2009, when Saturn was at a distance of roughly 1.25 billion kilometres from Earth. Hubble can see details as small as 300 kilometres across on Saturn.

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

44. Sequences of star formation in neighbouring galaxy

The iridescent tapestry of star birth in a neighbouring galaxy is captured in this panoramic view of glowing gas, dark dust clouds, and young, hot stars. The star-forming region, catalogued as N11B lies in the Large Magellanic Cloud (LMC), located only 160,000 light-years from Earth. With its high resolution, the Hubble Space Telescope is able to view details of star formation in the LMC as easily as ground-based telescopes are able to observe stellar formation within our own Milky Way.

Our neighbourhood galaxy lies in the Constellation of Dorado and is sprinkled with a number of regions harbouring recent and ongoing star formation. One of these star-forming region, N11B, is shown in this Hubble image. It is a subregion within a larger area of star formation called N11.

Credit: NASA/ESA and the Hubble Heritage Team (AURA/STScI/HEIC)

45. Playing twister

The Hubble telescope has captured an image of an unusual edge-on galaxy, revealing remarkable details of its warped dusty disk and showing how colliding galaxies spawn the formation of new generations of stars. The dust and spiral arms of normal spiral galaxies, like our own Milky Way, appear flat when viewed edge-on. This Hubble Heritage image of ESO 510-G13 shows a galaxy that, by contrast, has an unusual twisted disk structure.

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

46. Turquoise-tinted plumes

The brightly glowing plumes seen in this image are reminiscent of an underwater scene, with turquoise-tinted currents and nebulous strands reaching out into the surroundings.

However, this is no ocean. This image actually shows part of the Large Magellanic Cloud (LMC), a small nearby galaxy that orbits our galaxy and appears as a blurred blob in our skies. Hubble has peeked many times into this galaxy, releasing stunning images of the whirling clouds of gas and sparkling stars.

This image shows part of the Tarantula Nebula's outskirts. This famously beautiful nebula, located within the LMC, is a frequent target for Hubble.

Credit: ESA/Hubble & NASA

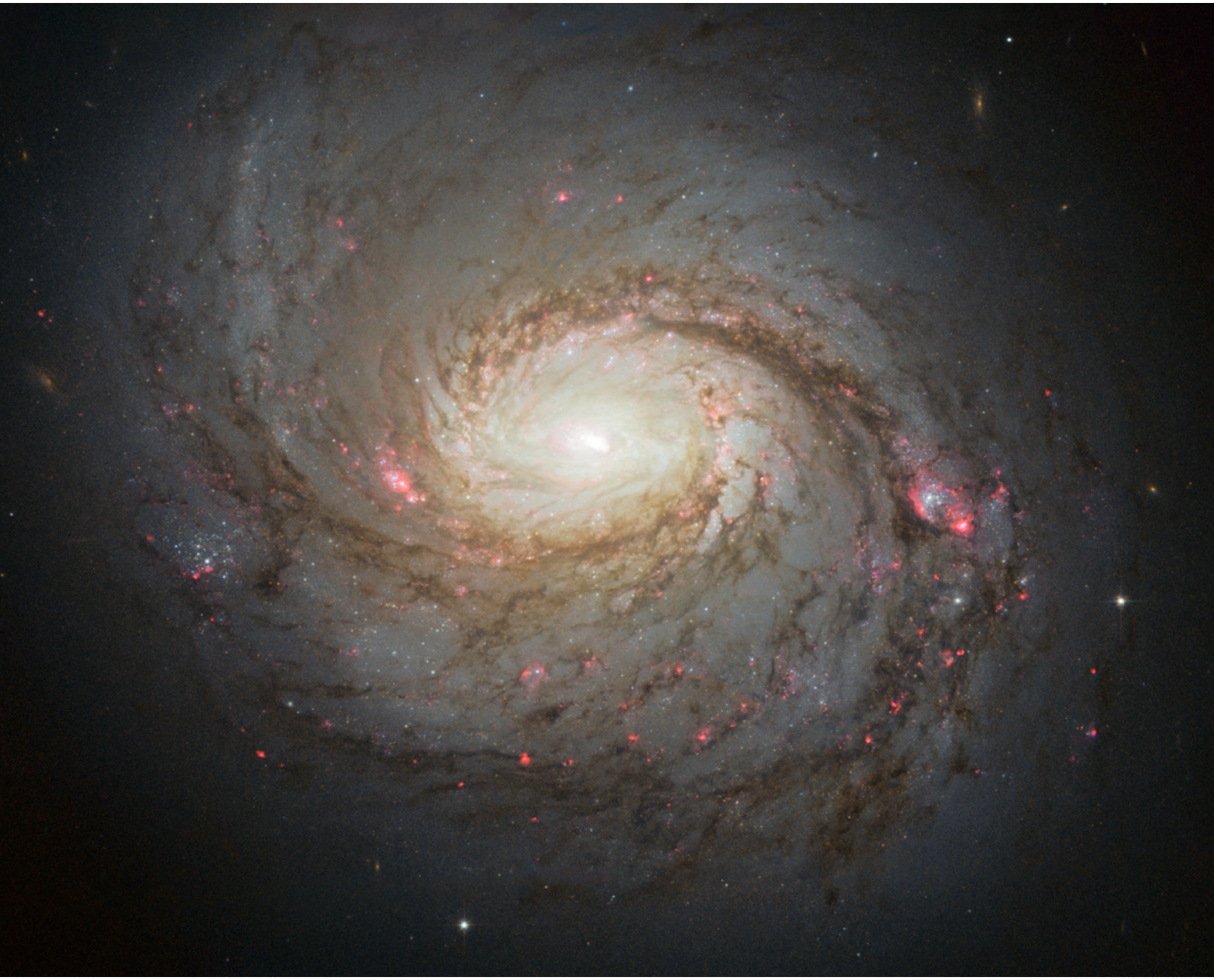
47. Monkey Head Nebula

To celebrate its 24th year in orbit, the Hubble Space Telescope has released this beautiful image of part of NGC 2174, also known as the Monkey Head Nebula.

NGC 2174 lies about 6400 light-years away in the constellation of Orion (The Hunter). Hubble previously viewed this part of the sky back in 2011 — the colourful region is filled with young stars embedded within bright wisps of cosmic gas and dust.

This portion of the Monkey Head Nebula was imaged in the infrared using Hubble's Wide Field Camera 3.

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



48. Pinwheeling arms of Messier 77

The Hubble Space Telescope has captured this vivid image of spiral galaxy Messier 77 — a galaxy in the constellation of Cetus, some 45 million light-years away from us. The streaks of red and blue in the image highlight pockets of star formation along the pinwheeling arms, with dark dust lanes stretching across the galaxy's starry centre. The galaxy belongs to a class of galaxies known as Seyfert galaxies, which have highly ionised gas surrounding an intensely active centre.

Credit: NASA, ESA & A. van der Hoeven

"If you ask a random person to name a telescope, assuredly, the answer given is the Hubble Space Telescope. It's no wonder why. No other telescope has captured the sheer beauty and scale of the cosmos like the HST. Including the Hubble Deep Field, or the Pillars of Creation, observers have used the HST to produce some of the most dramatic and iconic images of celestial targets ever taken. Those and many other famous images showcase the HST's unprecedented clarity and sensitivity, unmatched even by the best of HST's rivals. It is those qualities that make the HST one of the most important astronomical tools ever developed."

— Dr. Wesley Fraser

Plaskett Fellow
Herzberg Institute of Astrophysics
Victoria, BC, Canada

49. Spectacular view of Centaurus A

Centaurus A, also known as NGC 5128, is well known for its dramatic dusty lanes of dark material. Hubble's new observations, using its most advanced instrument, the Wide Field Camera 3, are the most detailed ever made of this galaxy. They have been combined here in a multi-wavelength image which reveals never-before-seen detail in the dusty portion of the galaxy.

As well as features in the visible spectrum, this composite shows ultraviolet light, which comes from young stars, and near-infrared light, which lets us glimpse some of the detail otherwise obscured by the dust.

Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration

"Hubble's predecessor in many ways was a little telescope called International Ultraviolet Explorer. When it was deactivated in 1996, its final observation was a repeat of its first observation in 1978. We'd like to see Hubble do the same thing, repeat its first observation."

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland

50. Abell 2218

The picture shows Abell 2218, a rich galaxy cluster composed of thousands of individual galaxies. It sits about 2.1 billion light-years from the Earth (redshift 0.17) in the northern constellation of Draco. When used by astronomers as a powerful gravitational lens to magnify distant galaxies, the cluster allows them to peer far into the Universe. However, it not only magnifies the images of hidden galaxies, but also distorts them into long, thin arcs.

Several arcs in the image can be studied in detail thanks to Hubble's sharp vision. Multiple distorted images of the same galaxies can be identified by comparing the shape of the galaxies and their colour. In addition to the giant arcs, many smaller arclets have been identified.

Credit: NASA, ESA, and Johan Richard (Caltech, USA)

"I'm a co-investigator on 3D-HST, a spectroscopic Hubble Treasury Program, mapping the third dimension of distance for thousands of galaxies across 85% of cosmic time. Together with another large imaging Treasury Program, CANDELS, these projects serve as the premier extragalactic surveys in the sky. With thousands of orbits invested by the Hubble Space Telescope, as well as at other wavelengths across the electromagnetic spectrum, CANDELS and 3D-HST have revolutionized our understanding of galaxy formation.*

"I've also been involved with studying the strong gravitationally-lensed actively star-forming galaxy RCS0327. Gravitational lensing affords us the opportunity to see significantly more details than could ever be achieved for unlensed galaxies. RCS0327 serves as a unique laboratory to study the physical properties of a galaxy existing at the peak of cosmic star formation, only a few billion years after the Big Bang."

— Dr. Katherine E. Whitaker

NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

** http://hubblesite.org/newscenter/archive/releases/2013/45/full/*

51. Reflection Nebula in Orion

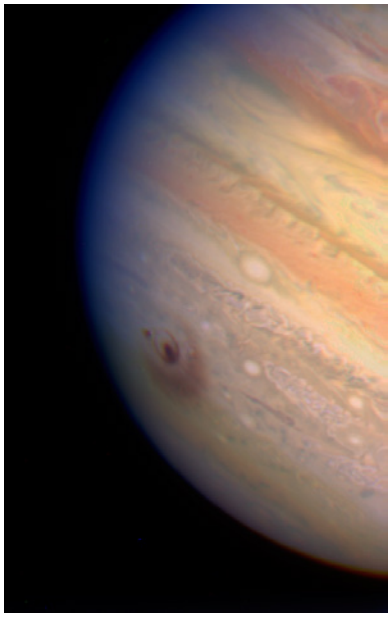
Just weeks after NASA astronauts repaired the Hubble Space Telescope in December 1999, the Hubble Heritage Project snapped this picture of NGC 1999, a nebula in the constellation Orion. The Heritage astronomers, in collaboration with scientists in Texas and Ireland, used Hubble's Wide Field Planetary Camera 2 (WFPC2) to obtain this colour image.

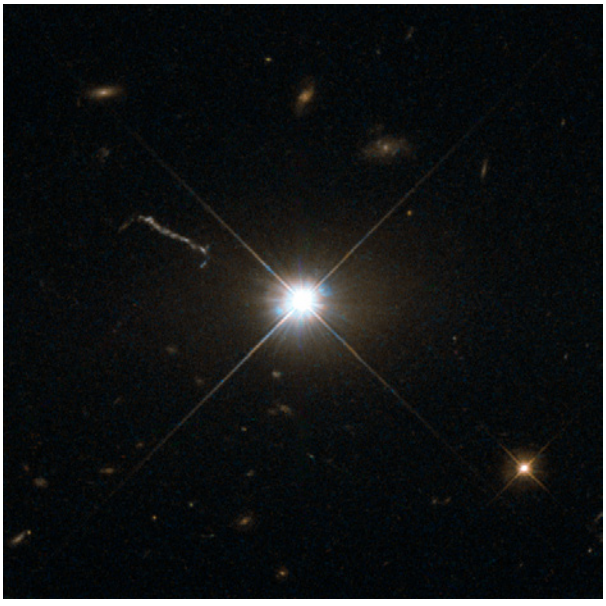
Credit: NASA/ESA and the Hubble Heritage Team (STScI)

52. Jupiter impact zones from comet

This true colour image of the giant planet Jupiter, by NASA and ESA's Hubble Space Telescope, reveals the impact sites of fragments 'D' and 'G' from Comet Shoemaker-Levy 9.

Credit: H. Hammel, MIT and NASA/ESA





53. Bright quasar 3C 273

This image is likely the best of ancient and brilliant quasar 3C 273, which resides in a giant elliptical galaxy in the constellation of Virgo (The Virgin). Its light has taken some 2.5 billion years to reach us. Despite this great distance, it is still one of the closest quasars to our home. It was the first quasar ever to be identified, and was discovered in the early 1960s by astronomer Allan Sandage.

The term quasar is an abbreviation of the phrase "quasi-stellar radio source", as they appear to be star-like on the sky. In fact, quasars are the intensely powerful centres of distant, active galaxies, powered by a huge disc of particles surrounding a supermassive black hole. As material from this disc falls inwards, some quasars — including 3C 273 — have been observed to fire off super-fast jets into the surrounding space. In this picture, one of these jets appears as a cloudy streak, measuring some 200 000 light-years in length.

Credit: ESA/Hubble & NASA

54. Gaseous streamers flutter in stellar breeze

N44C is the designation for a region of ionized hydrogen gas surrounding an association of young stars in the Large Magellanic Cloud (LMC), a nearby, small companion galaxy to the Milky Way visible from the Southern Hemisphere. N44C is part of the larger N44 complex, which includes young, hot, massive stars, nebulae, and a 'superbubble' blown out by multiple supernova explosions.

Credit: NASA/ESA and The Hubble Heritage Team

55. Remarkable double cluster

Located in the Large Magellanic Cloud, one of our neighbouring dwarf galaxies, this young globular-like star cluster is surrounded by a pattern of filamentary nebulosity that is thought to have been created during supernova blasts. It consists of a main globular cluster in the centre and a younger, smaller cluster, seen below and to the right, composed of extremely hot, blue stars and fainter, red T-Tauri stars. This wide variety of stars allows a thorough study of star formation processes.

Credit: ESA, NASA and Martino Romaniello (European Southern Observatory, Germany)

"Just last year, we carried out a massive program, one of Hubble's largest, in which we obtained a series of spectra of an active galaxy, a quasar-like object with a central black hole that is actively accreting mass.

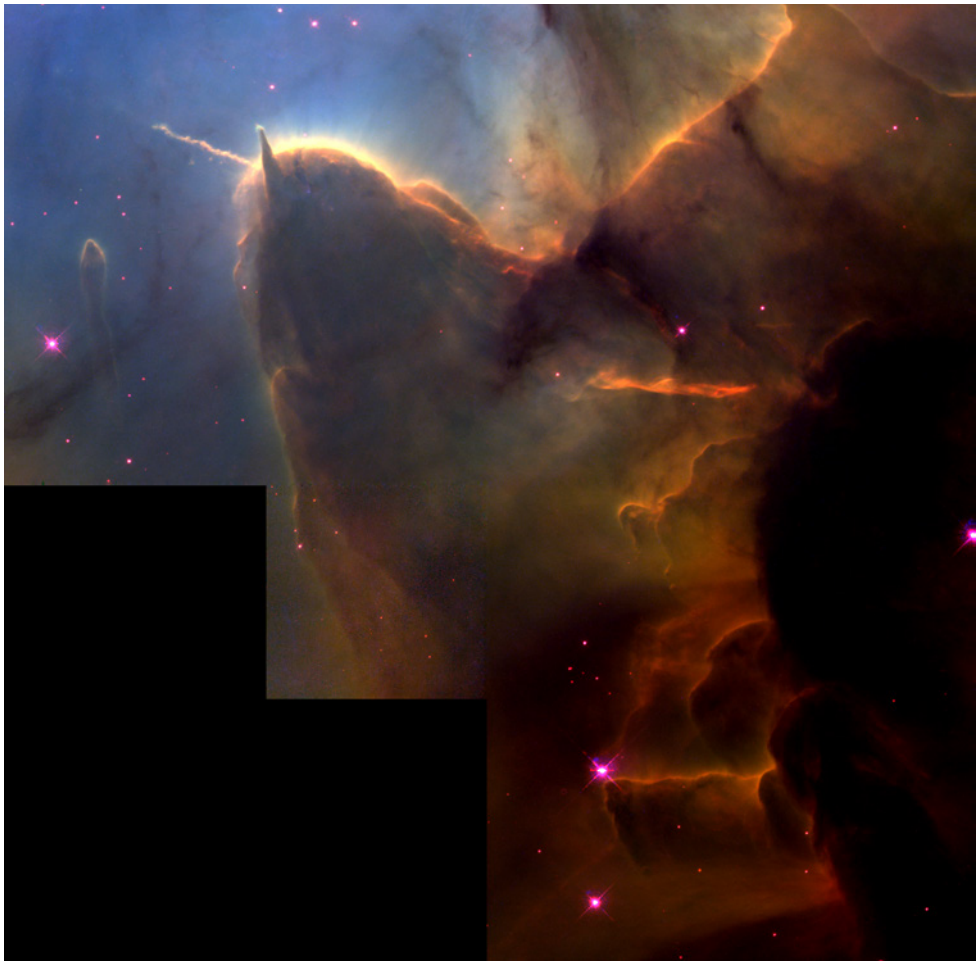
"We obtained one observation per day for half a year, allowing us to make a movie of how it evolves with time and how its inner structure changes.

"The data are beautiful and we're only now in the early stages of trying to interpret it."

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland



56 Stellar sibling rivalry of the Trifid Nebula

Massive newborn stars are creating in this dramatic torn apart image of the Trifid Nebula.The Trifid Nebula is home to many thousands of newly created stars. The source of the jet is a young very hot star buried in the cloud.

This Hubble Space Telescope image of the Trifid Nebula reveals a stellar nursery being torn apart by radiation from a nearby, massive star.

The picture also provides a peek at embryonic stars forming within an ill-fated cloud of dust and gas, which is destined to be eaten away by the glare from the massive neighbor.

This stellar activity is a beautiful example of how the life cycles of stars like our Sun is intimately connected with their more powerful siblings.

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

57. Violent history of NGC 7714

NGC 7714 is a spiral galaxy 100 million light-years from Earth — a relatively close neighbour in cosmic terms.

The galaxy has witnessed some violent and dramatic events in its recent past. Tell-tale signs of this brutality can be seen in NGC 7714's strangely shaped arms, and in the smoky golden haze that stretches out from the galactic centre — caused by an ongoing merger with its smaller galactic companion NGC 7715, which is out of the frame of this image.

Credit: ESA, NASA

58. Spiral galaxy M81

This Hubble Space Telescope photo shows the majestic spiral galaxy M81.

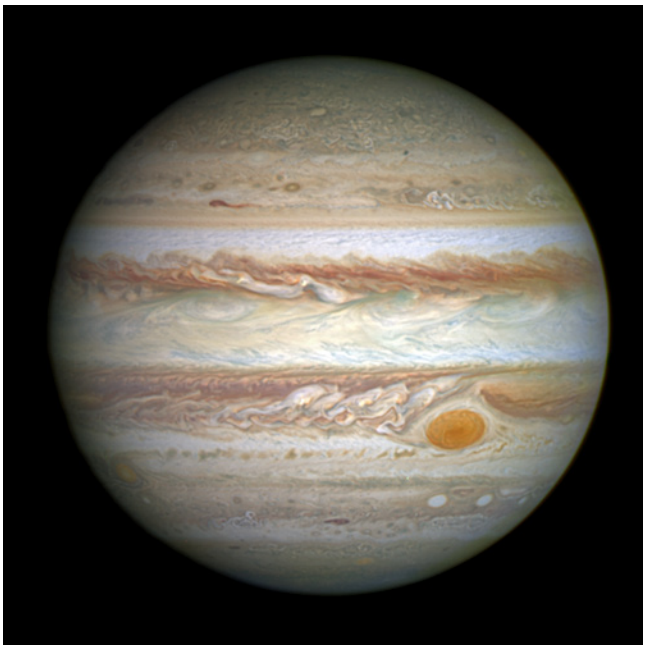
In the midsts of this galaxy is the supernova 1993J which was recently found to have a companion star which had been hidden in the glow of the supernova for 21 years.

Credit: NASA, ESA, A. Zezas (CfA), and A. Filippenko (UC Berkeley)

59. Jupiter and its shrunken Great Red Spot

This full-disc image of Jupiter was taken on 21 April 2014 with Hubble's Wide Field Camera 3 (WFC3).

Credit: NASA, ESA, and A. Simon (Goddard Space Flight Center)



60. Variable star RS Puppis

This Hubble image shows RS Puppis, a type of variable star known as a Cepheid variable. As variable stars go, Cepheids have comparatively long periods — RS Puppis, for example, varies in brightness by almost a factor of five every 40 or so days.

RS Puppis is unusual; this variable star is shrouded by thick, dark clouds of dust enabling a phenomenon known as a light echo to be shown with stunning clarity.

These Hubble observations show the ethereal object embedded in its dusty environment, set against a dark sky filled with background galaxies.

Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-Hubble/ Europe Collaboration

64. Carina Nebula

Composed of gas and dust, the pictured pillar resides in a tempestuous stellar nursery called the Carina Nebula, located 7500 light-years away in the southern constellation of Carina.

Taken in visible light, the image shows the tip of the three-light-year-long pillar, bathed in the glow of light from hot, massive stars off the top of the image. Scorching radiation and fast winds (streams of charged particles) from these stars are sculpting the pillar and causing new stars to form within it. Streamers of gas and dust can be seen flowing off the top of the structure.

Hubble's Wide Field Camera 3 observed the Carina Nebula on 24-30 July 2009. WFC3 was installed aboard Hubble in May 2009 during Servicing Mission 4. The composite image was made from filters that isolate emission from iron, magnesium, oxygen, hydrogen and sulphur.

These Hubble observations of the Carina Nebula are part of the Hubble Servicing Mission 4 Early Release Observations.

Credit: NASA, ESA and the Hubble SM4 ERO Team

62. Abell 1703

Located in the northern celestial hemisphere, Abell 1703 is composed of over one hundred different galaxies that act as a powerful cosmic telescope, or gravitational lens. The gravitational lens produced by the massive galaxy cluster in the foreground (the yellow mostly elliptical galaxies scattered across the image) bends the light rays in a way that can stretch the images and so amplify the brightness of the light rays from more distant galaxies. In the process it distorts their shapes and produces multiple banana-shaped images of the original galaxies. The result is the stunning image seen here - a view deeper into the Universe than possible with current technology alone. Abell 1703 is located at 3 billion light-years from the Earth (redshift 0.26).

Credit: NASA, ESA, and Johan Richard (Caltech, USA)

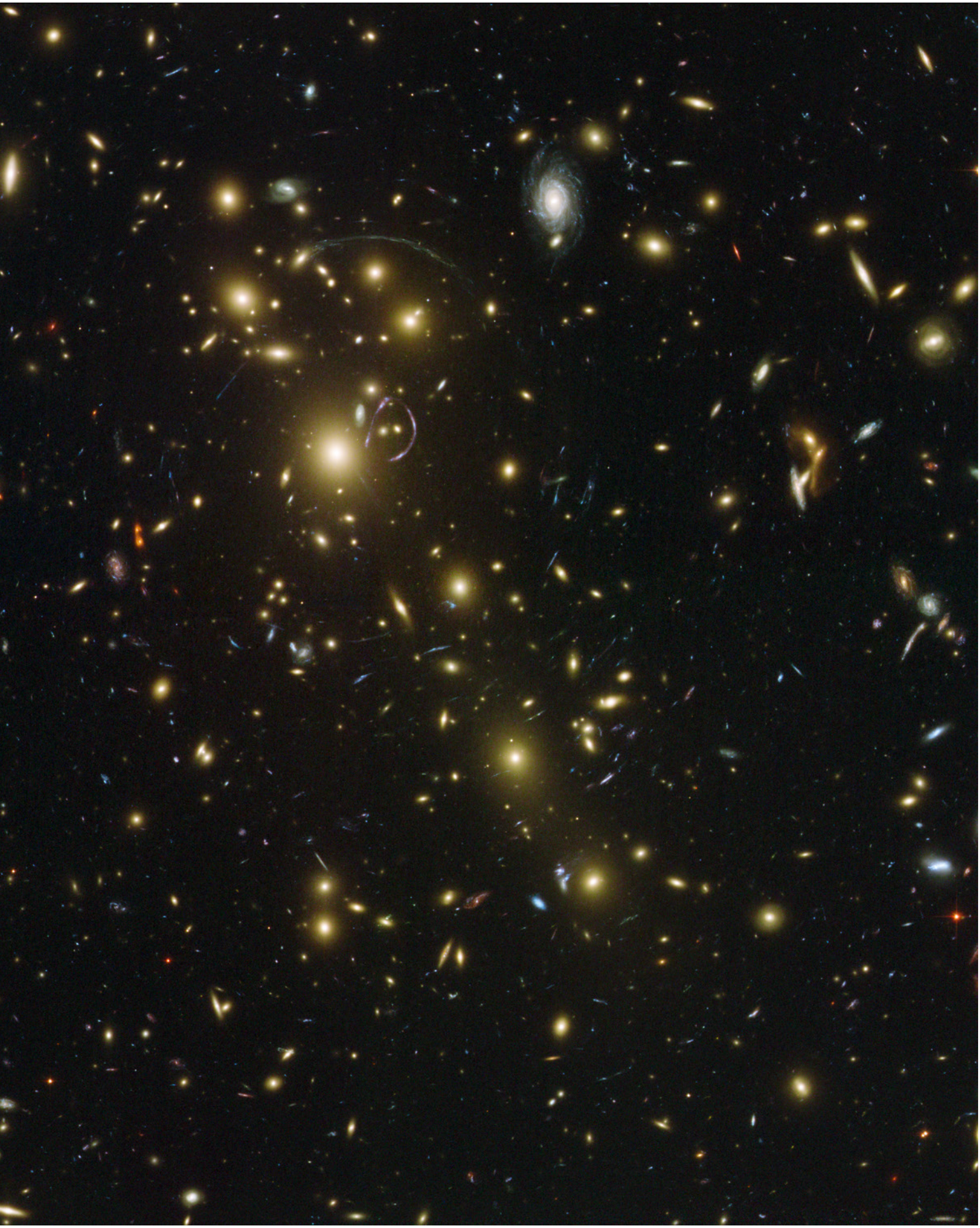
"The Hubble Space Telescope is the greatest astronomical instrument yet created by humankind. Since its launch 25 years ago, it has provided discoveries well beyond what we expected to learn.

"Some of the most dramatic discoveries have been of distant galaxies in the early universe. Due to the bright emission in the near-infrared from our Earth's atmosphere, only Hubble can obtain the deep imaging necessary to discover galaxies hailing from less than one billion years after the Big Bang. These observations over the past few years have proved astounding – the early universe is teeming with galaxies!

"This is one of Hubble's lasting legacies – a small telescope, with a mirror the size of your typical NBA center – can teach us about how galaxies are growing only 500 million years after the Big Bang. This is one dramatic bang for your buck!"

— Dr. Steven Finkelstein

Assistant Professor of Astronomy
University of Texas at Austin



63. The beautiful side of IC 335

This Hubble Space Telescope image shows the galaxy IC 335 in front of a backdrop of distant galaxies. IC 335 is part of a galaxy group containing three other galaxies, and located in the Fornax Galaxy Cluster 60 million light-years away.

As seen in this image, the disc of IC 335 appears edge-on from the vantage point of Earth. This makes it harder for astronomers to classify it, as most of the characteristics of a galaxy's morphology — the arms of a spiral or the bar across the centre — are only visible on its face. Still, the 45 000 light-year-long galaxy could be classified as an S0 type.

These lenticular galaxies are an intermediate state in galaxy morphological classification schemes between true spiral and elliptical galaxies. They have a thin stellar disc and a bulge, like spiral galaxies, but in contrast to typical spiral galaxies they have used up most of the interstellar medium. Only a few new stars can be created out of the material that is left and the star formation rate is very low. Hence, the population of stars in S0 galaxies consists mainly of aging stars, very similar to the star population in elliptical galaxies.

As S0 galaxies have only ill-defined spiral arms they are easily mistaken for elliptical galaxies if they are seen inclined face-on or edge-on as IC 335 here. And indeed, despite the morphological differences between S0 and elliptical class galaxies, they share a some common characteristics, like typical sizes and spectral features.

Both classes are also early-type galaxies, as they are evolving passively. However, elliptical galaxies may be passively evolving when we observe them, but they had violent interactions with other galaxies in their past. Whereas S0 galaxies are either aging and fading spiral galaxies, which never had any interactions with other galaxies, or they are the aging result of a single merger between two spiral galaxies in the past. The exact nature of these galaxies is still a matter of debate.

Credit: ESA/Hubble & NASA

"I think the most important discoveries made by Hubble have always been the unanticipated ones. For example, Hubble played a role in the discovery of dark energy and the accelerating universe. Hubble has also allowed astronomers to study the evolution of galaxies over most of cosmic history, revealing that galaxies in the early universe look remarkably different from local galaxies."

— Dr. Katherine E. Whitaker

NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

64. Whirling disc of NGC 4526

This neat little galaxy is known as NGC 4526. Its dark lanes of dust and bright diffuse glow make the galaxy appear to hang like a halo in the emptiness of space in this image from Hubble.

Although this image paints a picture of serenity, the galaxy is anything but. It is one of the brightest lenticular galaxies known, a category that lies somewhere between spirals and ellipticals. It has hosted two known supernova explosions, one in 1969 and another in 1994, and is known to have a colossal supermassive black hole at its centre that has the mass of 450 million Suns.

NGC 4526 is part of the Virgo cluster of galaxies. Ground-based observations of galaxies in this cluster have revealed that a quarter of these galaxies seem to have rapidly rotating discs of gas at their centres. The most spectacular of these is this galaxy, NGC 4526, whose spinning disc of gas, dust, and stars reaches out uniquely far from its heart, spanning some 7% of the galaxy's entire radius.

This disc is moving incredibly fast, spinning at more than 250 kilometres per second. The dynamics of this quickly whirling region were actually used to infer the mass of NGC 4526's central black hole — a technique that had not been used before to constrain a galaxy's central black hole.

This image was taken using Hubble's Wide Field Planetary Camera 2.

Credit: ESA/Hubble & NASA

"It's the sharpness, depth, and details in the images. So much better than anything ever taken from the ground."

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland

65. Star-forming region S106

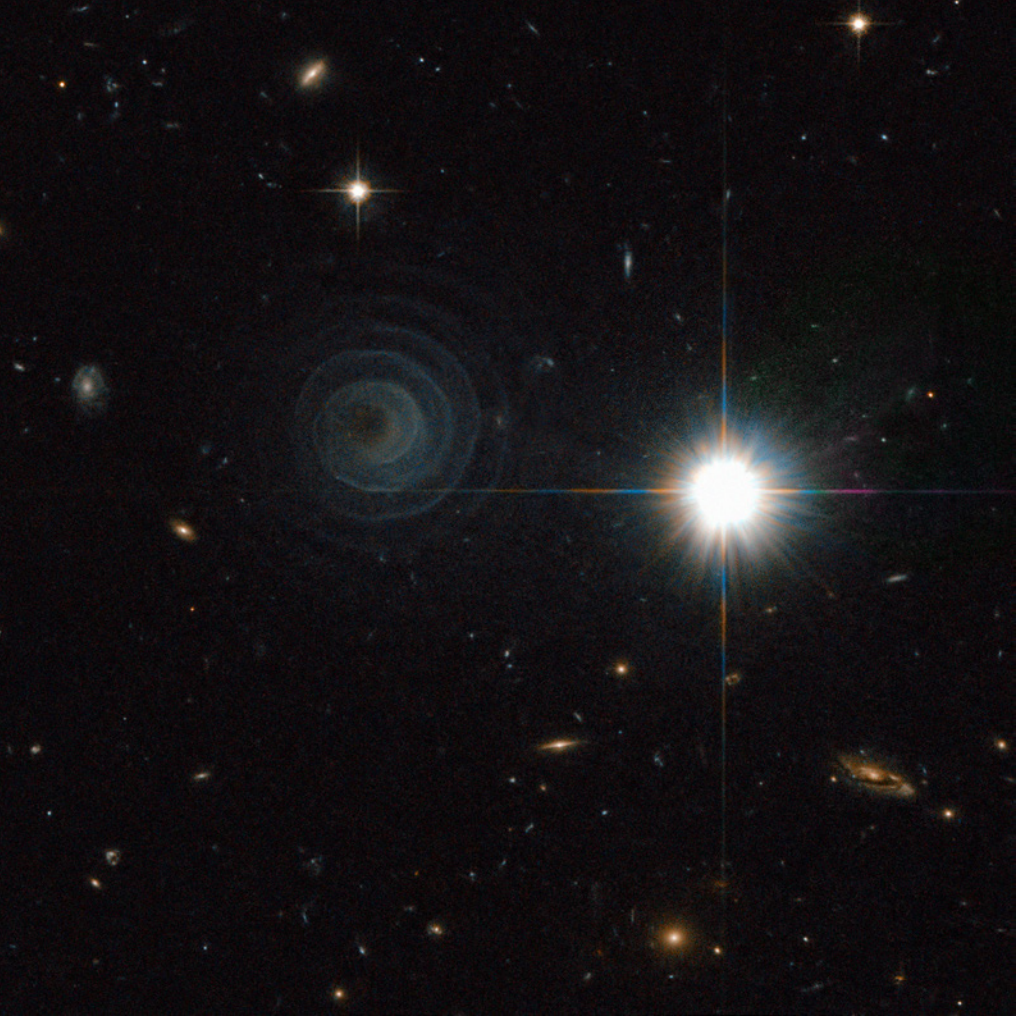
This image shows Sh 2-106, or S106 for short. This is a compact star forming region in the constellation Cygnus (The Swan). A newly-formed star called S106 IR is shrouded in dust at the centre of the image, and is responsible for the surrounding gas cloud's hourglass-like shape and the turbulence visible within. Light from glowing hydrogen is coloured blue in this image.

Credit: NASA & ESA

"Hubble is much more than a telescope, or a satellite: it is an outstanding masterpiece of human achievement. Not only do its spectacular pictures shape the way we think about the Universe, but at the same time the enormous efforts of the engineers and astronauts which kept it in orbit, and made it ever more powerful, are an unrivalled source of inspiration."

— Boris Gänsicke

Professor in the Department of Physics
University of Warwick
Coventry, United Kingdom



66. Extraordinary celestial spiral

This remarkable picture shows one of the most perfect geometrical forms created in space. It captures the formation of an unusual pre-planetary nebula, known as IRAS 23166+1655, around the star LL Pegasi (also known as AFGL 3068) in the constellation of Pegasus (the Winged Horse).

The striking picture shows what appears to be a thin spiral pattern of astonishingly regularity winding around the star, which is itself hidden behind thick dust. The material forming the spiral is moving outwards a speed of about 50 000 km/hour . Astronomers calculate that the shells are each separated by about 800 years.

The spiral is thought to arise because LL Pegasi is a binary system, with the star that is losing material and a companion star orbiting each other. The spacing between layers in the spiral is expected to directly reflect the orbital period of the binary, which is indeed estimated to be also about 800 years.

Credit: ESA/NASA & R. Sahai

67. Stripping away at NGC 4522

Hubble allows astronomers to study an interesting and important phenomenon called ram pressure stripping that is so powerful, it is capable of mangling galaxies and even halting their star formation.

NGC 4522 is a spectacular example of a spiral galaxy that is currently being stripped of its gas content. Hubble's view practically swirls off the page with apparent movement. It highlights the dramatic state of the galaxy with an especially vivid view of the ghostly gas being forced out of it. Bright blue pockets of new star formation can be seen to the right and left of centre.

Credit: NASA & ESA

68. Pair of mammoth stars

The image shows a pair of colossal stars, WR 25 and Tr16-244, located within the open cluster Trumpler 16. This cluster is embedded within the Carina Nebula, an immense cauldron of gas and dust that lies approximately 7500 light-years from Earth in the constellation of Carina, the Keel. WR 25 is the brightest, situated near the centre of the image. The neighbouring Tr16-244 is the third brightest, just to the upper left of WR 25. The second brightest, to the left of WR 25, is a low mass star located much closer to the Earth than the Carina Nebula.

Credit: NASA, ESA and Jesús Maíz Apellániz (Instituto de Astrofísica de Andalucía, Spain)

"The most fascinating things we are learning from Hubble in my area of expertise is the study of the most massive stars. These stars are very rare and have very short lives, astronomically speaking, 'just a few million years'. This is because they are extremely bright, up to a million times brighter than our own star the Sun, which means that they quickly consume all their fuel.

"Their fuel consists of hydrogen at first, which they burn into helium and later carbon and oxygen and heavier elements. These are the elements that we ourselves are made of. The oxygen you breath while reading this was ones made in the deep interior of a massive star. Even the tissues that make up your muscles and bones was ones star dust created when a massive star died and exploded.

"One of the big questions astronomers try to answer is how massive is the most massive star. This is a surprisingly hard question to answer. The theoretical models do not give a clear answer.

"The only way to answer this questions is with observations. Unfortunately massive stars live in very crowded regions and they shine most of their light in the ultra violet which is blocked by our atmosphere. Here is were the Hubble Telescope made a major difference. Being in space above the atmosphere it can freely observe in colors that are inaccessible from the ground. In addition the superb resolution allows us to look into the centers of some of the densest star clusters."

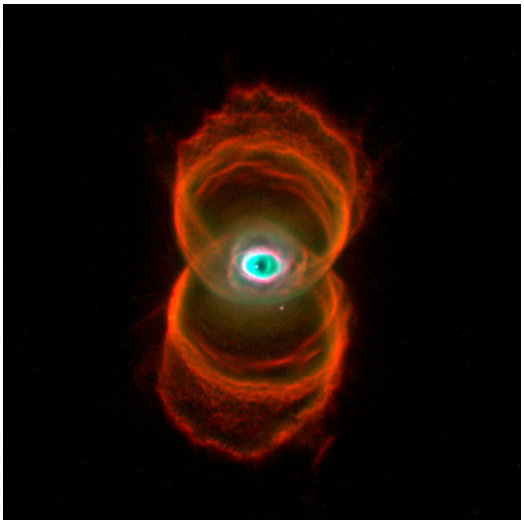
— Dr. Selma E. de Mink

Assistant Professor
University of Amsterdam
Netherlands

69. WR 25 and Tr16-244

WR 25 and Tr16-244, at the bottom of the image, are located within the open cluster Trumpler 16. This cluster is embedded within the Carina Nebula, an immense cauldron of gas and dust that lies approximately 7500 light-years from Earth in the constellation of Carina, the Keel. At the top of the image, a peculiar nebula with the shape of a "defiant" finger points towards WR25 and Tr16-244.

Credit: NASA, ESA and Jesús Maíz Apellániz (Instituto de Astrofísica de Andalucía, Spain)



70. Hourglass Nebula

This Hubble image reveals the true shape of MyCn18, a young planetary nebula located about 8,000 light-years away, to be an hourglass with an intricate pattern of 'etchings' in its walls.

The results are of great interest because they shed new light on the poorly understood ejection of stellar matter which accompanies the slow death of Sun-like stars. In previous ground-based images, MyCn18 appears to be a pair of large outer rings with a smaller central one, but the fine details cannot be seen.

Credit: Raghvendra Sahai and John Trauger (JPL), the WFPC2 science team, and NASA/ESA

71 A galaxy on the edge

The bright streak slicing across the frame of this spectacular image is an edge-on view of galaxy NGC 4762, and a number of other distant galaxies can be seen scattered in the background.

Previously thought to be a barred spiral galaxy, NGC 4762 has since been found to be a lenticular galaxy, a kind of intermediate step between an elliptical and a spiral. The edge-on view that we have of this particular galaxy makes it difficult to determine its true shape.

The galaxy's disc is asymmetric and warped, which could potentially be explained by NGC 4762 violently cannibalising a smaller galaxy in the past. The remains of this former companion may then have settled within NGC 4762's disc, redistributing the gas and stars and so changing the disc's morphology.

Credit: ESA/Hubble & NASA

72. The Hubble eXtreme Deep Field

This image, called the Hubble eXtreme Deep Field (XDF), combines Hubble observations taken over the past decade of a small patch of sky in the constellation of Fornax. With a total of over two million seconds of exposure time, it is the deepest image of the Universe ever made, combining data from previous images including the Hubble Ultra Deep Field (taken in 2002 and 2003) and Hubble Ultra Deep Field Infrared (2009).

The image covers an area less than a tenth of the width of the full Moon, making it just a 30 millionth of the whole sky. Yet even in this tiny fraction of the sky, the long exposure reveals about 5500 galaxies, some of them so distant that we see them when the Universe was less than 5% of its current age.

The Hubble eXtreme Deep Field image contains several of the most distant objects ever identified.

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

73. Panoramic view of a star-forming region

30 Doradus is the brightest star-forming region in our galactic neighbourhood and home to the most massive stars ever seen. The nebula resides 170 000 light-years away in the Large Magellanic Cloud, a small, satellite galaxy of our Milky Way. No known star-forming region in our galaxy is as large or as prolific as 30 Doradus.

The image comprises one of the largest mosaics ever assembled from Hubble photos and includes observations taken by Hubble's Wide Field Camera 3 and Advanced Camera for Surveys, combined with observations from the European Southern Observatory's MPG/ESO 2.2-metre telescope which trace the location of glowing hydrogen and oxygen.

The image was released to celebrate Hubble's 22nd anniversary.

Credit: NASA, ESA, ESO, D. Lennon and E. Sabbi (ESA/STScI), J. Anderson, S. E. de Mink, R. van der Marel, T. Sohn, and N. Walborn (STScI), N. Bastian (Excellence Cluster, Munich), L. Bedin (INAF, Padua), E. Bressert (ESO), P. Crowther (Sheffield), A. de Koter (Amsterdam), C. Evans (UKATC/STFC, Edinburgh), A. Herrero (IAC, Tenerife), N. Langer (AifA, Bonn), I. Platais (JHU) and H. Sana (Amsterdam)

"A satellite galaxy of the Milky Way, the Large Magellanic Cloud, is hosting one of the most violent nearby regions of star formation. While I was at Space Telescope [STScI] we proposed to observe this region with Hubble and make one of the largest mosaic images that Hubble ever made.

"This program was lead by D. J. Lennon and E. Sabbi. The resulting image was not only scientifically very useful, it was also simply extremely beautiful. It was released as Hubble's 22nd birthday image.

"Looking at it on a computer screen does not do justice to this incredibly large image. It should really be printed and be several meters wide, so you can stand in front of it and fully appreciate it."

— Dr. Selma E. de Mink

Assistant Professor
University of Amsterdam
Netherlands

74. Huge star formation region N11 in the LMC

This broad vista of young stars and gas clouds in our neighbouring galaxy, the Large Magellanic Cloud, was captured by Hubble's Advanced Camera for Surveys (ACS). This region is named LHA 120-N 11, informally known as N11, and is one of the most active star formation regions in the nearby Universe. This picture is a mosaic of ACS data from five different positions and covers a region about six arcminutes across.

Credit: NASA, ESA and Jesús Maíz Apellániz (Instituto de Astrofísica de Andalucía, Spain)

"I entered the field of astronomy when Hubble was already in its 'prime' years, so it is hard for me to imagine a world without Hubble and the amazing discoveries that have resulted. Hubble has rewritten the textbooks, exploring all scales of the universe. Humanity would be at a great loss without the fundamental discoveries of the Hubble Space Telescope."

— Dr. Katherine E. Whitaker

NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

75. Heavyweight of the Leo Triplet

Hubble has snapped a spectacular view of M66, the largest "player" of the Leo Triplet, and a galaxy with an unusual anatomy: it displays asymmetric spiral arms and an apparently displaced core. The peculiar anatomy is most likely caused by the gravitational pull of the other two members of the trio.

The unusual spiral galaxy, Messier 66, is located at a distance of about 35 million light-years in the constellation of Leo. Together with Messier 65 and NGC 3628, Messier 66 is the member of the Leo Triplet, a trio of interacting spiral galaxies, part of the larger Messier 66 group. Messier 66 wins in size over its fellow triplets — it is about 100 000 light-years across.

Credit: NASA, ESA and the Hubble Heritage (STScI/ AURA)-ESA/Hubble Collaboration

76. Star on a Hubble diet

The star cluster Pismis 24 lies in the core of the large emission nebula NGC 6357 that extends one degree on the sky in the direction of the Scorpius constellation. Part of the nebula is ionised by the youngest (bluest) heavy stars in Pismis 24. The intense ultraviolet radiation from the blazing stars heats the gas surrounding the cluster and creates a bubble in NGC 6357. The presence of these surrounding gas clouds makes probing into the region even harder.

One of the top candidates for the title of "Milky Way stellar heavyweight champion" was, until now, Pismis 24-1, a bright young star that lies in the core of the small open star cluster Pismis 24 (the bright stars in the Hubble image) about 8,000 light-years away from Earth. Pismis 24-1 was thought to have an incredibly large mass of 200 to 300 solar masses. New Hubble measurements of the star, have, however, resolved Pismis 24-1 into two separate stars, and, in doing so, have "halved" its mass to around 100 solar masses.

Credit: NASA, ESA and Jesús Maíz Apellániz (Instituto de Astrofísica de Andalucía, Spain)

"Over the past 25 years, the HST, or Hubble to most astronomers, has revolutionized most fields of astronomical research, including studies of our own Solar System. This is especially true in astronomer's efforts to understand the denizens of the Kuiper Belt.

"Colloquially named after Gerard Kuiper, one of the first astronomers to propose the existence of the Kuiper Belt, the Kuiper Belt resides at and beyond the orbit of Neptune. Possessing as many as a few hundred dwarf planets including the most famous, Pluto, the Kuiper Belt presents an enigmatic picture of a population that was well on its way to forming a planet, but ultimately failed.

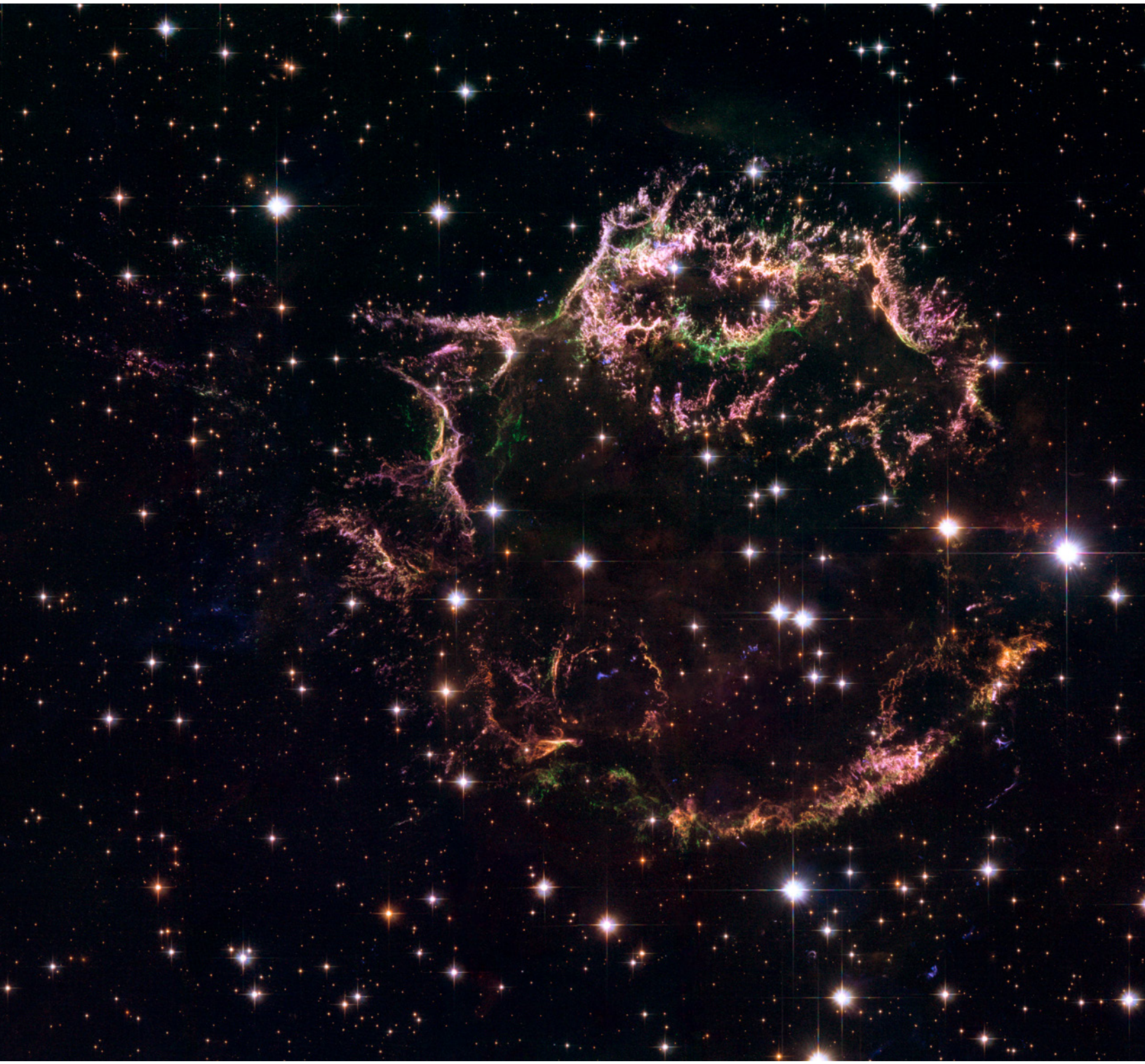
"Hubble has enabled many critical discoveries about the physical nature of Kuiper Belt objects. Most Kuiper Belt objects reside at more than 40 times further from the Sun than does the Earth. Due to their comparatively small sizes, those objects remain unresolved (or are only barely resolved) even to Hubble. As a result, HST images of KBOs are generally unremarkable.

"This isn't true however, for the Kuiper Belt's substantial binary population, the discovery of which is one of Hubble's key findings regarding the Kuiper Belt. Roughly 20% of KBOs are in binary, or higher multiplicity systems, including Pluto; beyond Charon, Pluto has four small satellites all of which were discovered in HST images – the image of Pluto and its siblings is one of my personal favorites**. By observing the motions of these multiple systems, astronomers have been able to directly measure the masses of these binary systems. Further, Hubble has helped reveal peculiar aspects of the formation of these systems, including: the massive collisions responsible for the formation of the satellite systems around the largest KBOs, like Pluto and his brother, Eris; or the currently unexplained coeval growth that smaller KBOs must have experienced to produce the nearly identical compositions found for each member of a given pair."*

— Dr. Wesley Fraser

Plaskett Fellow
Herzberg Institute of Astrophysics
Victoria, BC, Canada

* *http://hubblesite.org/newscenter/archive/releases/2002/04/*
** *http://hubblesite.org/newscenter/archive/releases/2012/32/*



77. Colourful aftermath of a violent stellar death

This image provides a detailed look at the tattered remains of a supernova explosion known as Cassiopeia A (Cas A). It is the youngest known remnant from a supernova explosion in the Milky Way. The new Hubble image shows the complex and intricate structure of the star's shattered fragments.

Credit: NASA, ESA, and the Hubble Heritage STScI/AURA)-ESA/Hubble Collaboration

"Hubble's lasting legacy will be that we HAVE to do certain types of astronomy from space. We will always need assets in space if astronomy is to advance."

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland

78. Nearby dust clouds in the Milky Way

The yearly ritual of spring cleaning clears a house of dust as well as dust "bunnies", those pesky dust balls that frolic under beds and behind furniture. Hubble has photographed similar dense knots of dust and gas in our Milky Way Galaxy. This cosmic dust, however, is not a nuisance. It is a concentration of elements that are responsible for the formation of stars in our galaxy and throughout the universe.

These opaque, dark knots of gas and dust are called Bok globules, and they are absorbing light in the center of the nearby emission nebula and star-forming region, NGC 281. The globules are named after astronomer Bart Bok, who proposed their existence in the 1940's.

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

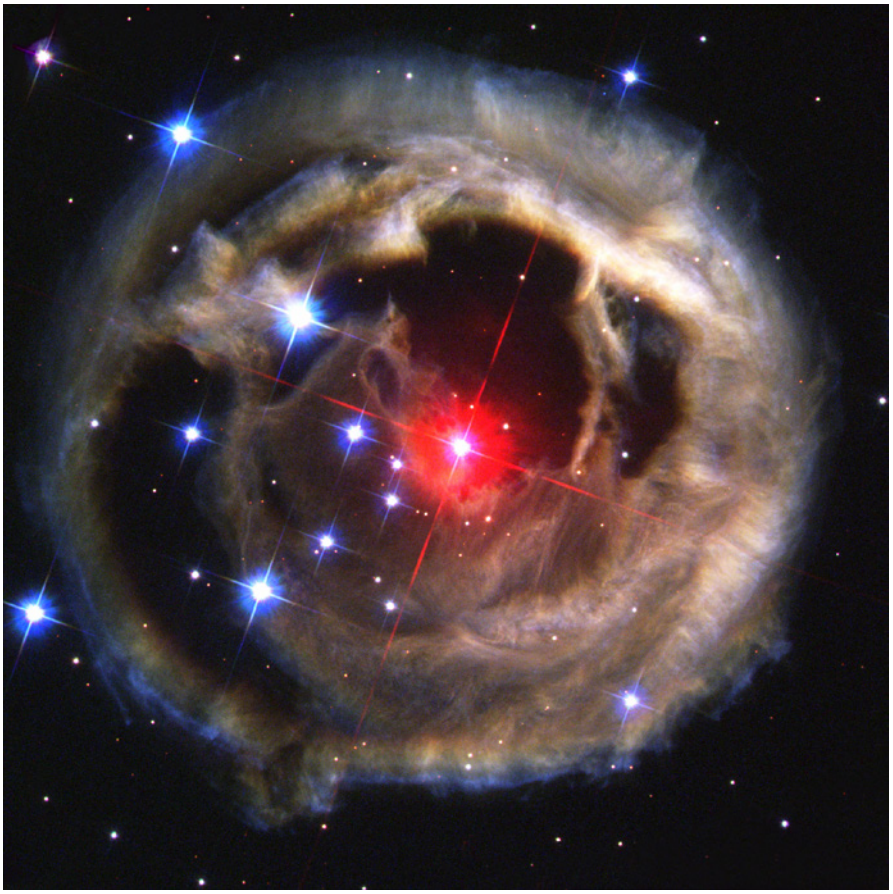
"Another critical discovery enabled by Hubble is the indirect discovery of an abundant population of small, roughly 1 km diameter Kuiper Belt objects. By virtue of their small sizes, KBOs smaller than ~10 km in diameter are too faint to be observed directly, even by the HST. Remarkably however, a pair of objects smaller than 1 km diameter have been observed by the Fine Guidance Sensors, detectors whose main purpose is to keep Hubble locked on the stars. Those sensors detected the shadows cast by the small Kuiper Belt objects as they passed in front of the stars Hubble was observing. While astronomers are still trying to understand the full significance of this discovery, it appears that these small bodies are the fragments produced during a state of significant collisional bombardment, a process that may have been partially responsible for the failure of the Kuiper Belt to form another full planet.*

"With its unique imaging capabilities, Hubble has enabled countless discoveries about the Kuiper Belt and the outer Solar System. The images it has taken of Pluto's surface and satellite family are just a sample of the iconic images captured in NASA's top 100 images produced by the Hubble Space Telescope. No other telescope has equally captured the wonder and imagination of the public and the astronomer alike, earning Hubble's place as not just the most influential telescope facility, but arguably the most influential science facility in general."

— Dr. Wesley Fraser

Plaskett Fellow
Herzberg Institute of Astrophysics
Victoria, BC, Canada

** http://hubblesite.org/newscenter/archive/releases/2009/33/full/*



79. Echo from mysterious erupting star (Dec. 2002 image)

This is the first in a sequence of four pictures from the NASA/ESA Hubble Space Telescope's Advanced Camera for Surveys that dramatically demonstrates the echoing of light through space caused by an unusual stellar outburst in January 2002.

The image was taken 17 December 2002. The image is combined from exposures taken through blue (B), green (V), and infrared (I) filters.

Credit: NASA, European Space Agency, and H.E. Bond (STScI)

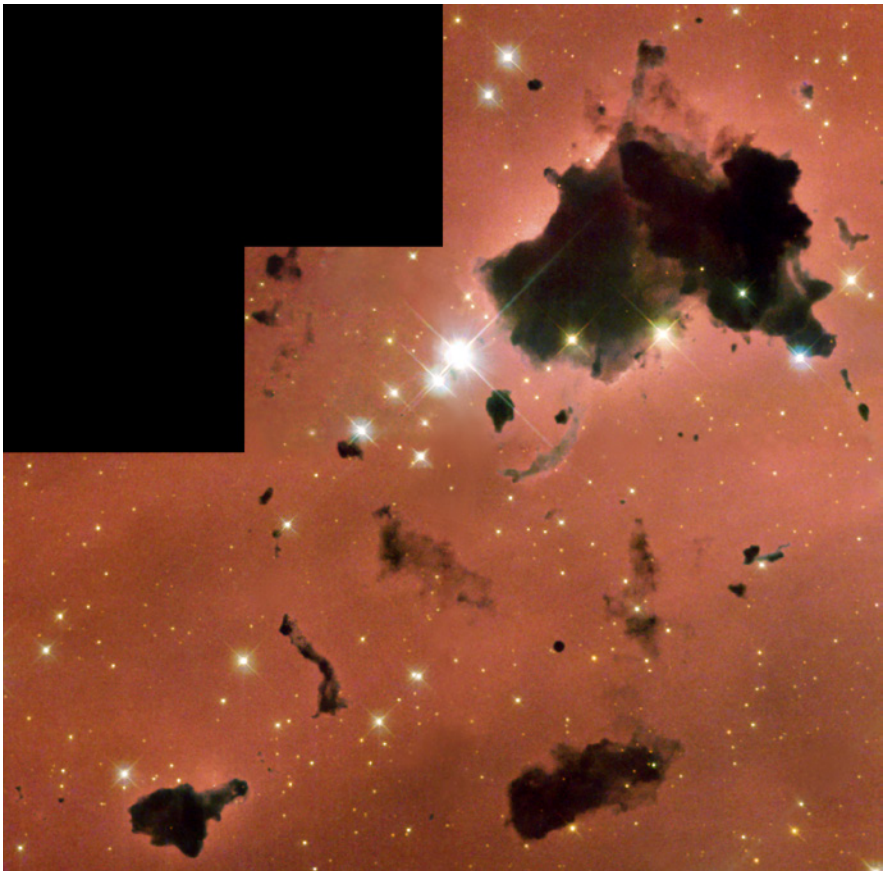
80. Thackeray's Globules

Strangely glowing dark clouds float serenely in this remarkable and beautiful image. These dense, opaque dust clouds - known as 'globules' - are silhouetted against nearby bright stars in the busy star-forming region, IC 2944.

Astronomer A.D. Thackeray first spied the globules in IC 2944 in 1950. Globules like these have been known since Dutch-American astronomer Bart Bok first drew attention to such objects in 1947.

But astronomers still know very little about their origin and nature, except that they are generally associated with areas of star formation, called 'HII regions' due to the presence of hydrogen gas. IC 2944 is filled with gas and dust that is illuminated and heated by a loose cluster of massive stars much hotter and more massive than our Sun.

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



81. The third way of galaxies

The subject of this image is NGC 6861, a galaxy discovered in 1826 by the Scottish astronomer James Dunlop. Almost two centuries later we now know that NGC 6861 is the second brightest member of a group of at least a dozen galaxies called the Telescopium Group.

This view shows some important details of NGC 6861. One of the most prominent features is the disc of dark bands circling the centre of the galaxy. These dust lanes are a result of large clouds of dust particles obscuring the light emitted by the stars behind them.

Dust lanes are very useful for working out whether we are seeing the galaxy disc edge-on, face-on or, as is the case for NGC 6861, somewhat in the middle. Dust lanes like these are typical of a spiral galaxy. The dust lanes are embedded in a white oval shape, which is made up of huge numbers of stars orbiting the centre of the galaxy. This oval is, rather puzzlingly, typical of an elliptical galaxy.

So which is it — spiral or elliptical? The answer is neither! NGC 6861 does not belong to either the spiral or the elliptical family of galaxies. It is a lenticular galaxy, a family which has features of both.

The relationships between these three kinds of galaxies are not yet well understood. A lenticular galaxy could be a faded spiral that has run out of gas and lost its arms, or the result of two galaxies merging.

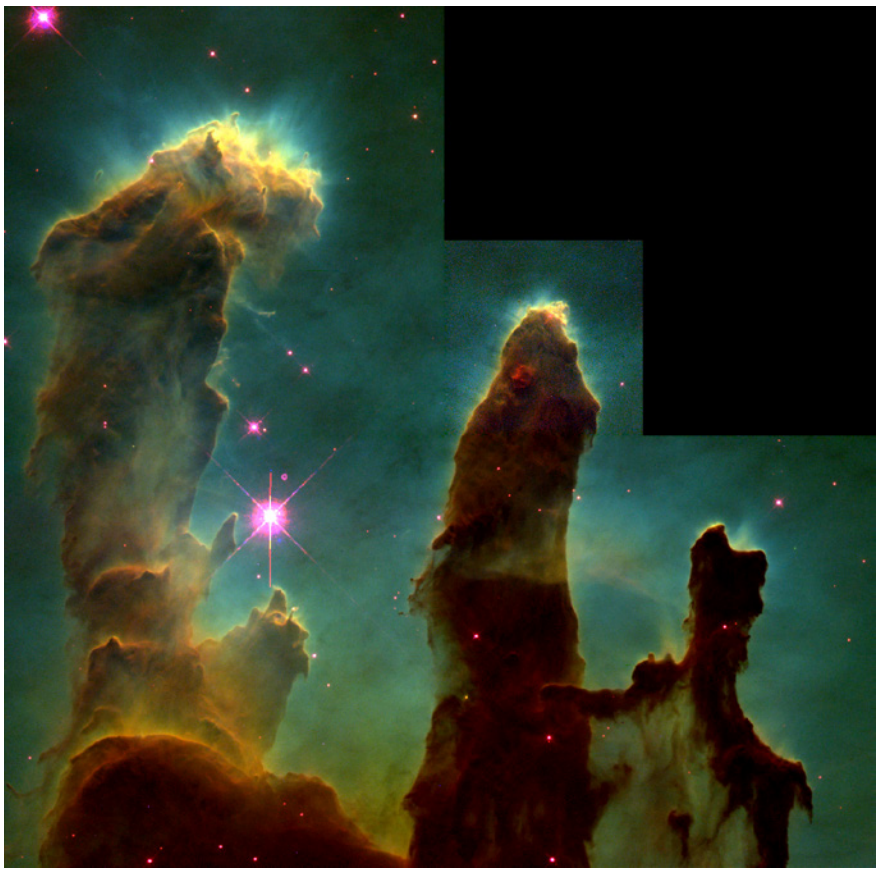
Credit: ESA/Hubble & NASA

82. Pillars of Creation

These columns that resemble stalagmites protruding from the floor of a cavern columns are in fact cool interstellar hydrogen gas and dust that act as incubators for new stars. Inside them and on their surface astronomers have found knots or globules of denser gas. These are called EGGs (acronym for "Evaporating Gaseous Globules"). Inside at least some of the EGGs stars being formed.

Undersea coral? Enchanted castles? Space serpents? These eerie, dark pillar-like structures are actually columns of cool interstellar hydrogen gas and dust that are also incubators for new stars. The pillars protrude from the interior wall of a dark molecular cloud like stalagmites from the floor of a cavern.

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



83. The oldest cluster in its cloud

This image shows NGC 121, a globular cluster in the constellation of Tucana (The Toucan). Globular clusters are big balls of old stars that orbit the centres of their galaxies like satellites — the Milky Way, for example, has around 150.

NGC 121 belongs to one of our neighbouring galaxies, the Small Magellanic Cloud (SMC). It was discovered in 1835 by English astronomer John Herschel, and in recent years it has been studied in detail by astronomers wishing to learn more about how stars form and evolve.

Stars do not live forever — they develop differently depending on their original mass. In many clusters, all the stars seem to have formed at the same time, although in others we see distinct populations of stars that are different ages. By studying old stellar populations in globular clusters, astronomers can effectively use them as tracers for the stellar population of their host galaxies. With an object like NGC 121, which lies close to the Milky Way, Hubble is able to resolve individual stars and get a very detailed insight.

NGC 121 is around 10 billion years old, making it the oldest cluster in its galaxy; all of the SMC's other globular clusters are 8 billion years old or younger. However, NGC 121 is still several billions of years younger than its counterparts in the Milky Way and in other nearby galaxies like the Large Magellanic Cloud. The reason for this age gap is not completely clear, but it could indicate that cluster formation was initially delayed for some reason in the SMC, or that NGC 121 is the sole survivor of an older group of star clusters.

This image was taken using Hubble's Advanced Camera for Surveys (ACS). A version of this image was submitted to the Hubble's Hidden Treasures image processing competition by contestant Stefano Campani.

Credit: ESA/Hubble & NASA

84. Barred spiral galaxy Messier 83

This new Hubble image shows the scatterings of bright stars and thick dust that make up spiral galaxy Messier 83, otherwise known as the Southern Pinwheel Galaxy. One of the largest and closest barred spirals to us, this galaxy is dramatic and mysterious; it has hosted a large number of supernova explosions, and appears to have a double nucleus lurking at its core.

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

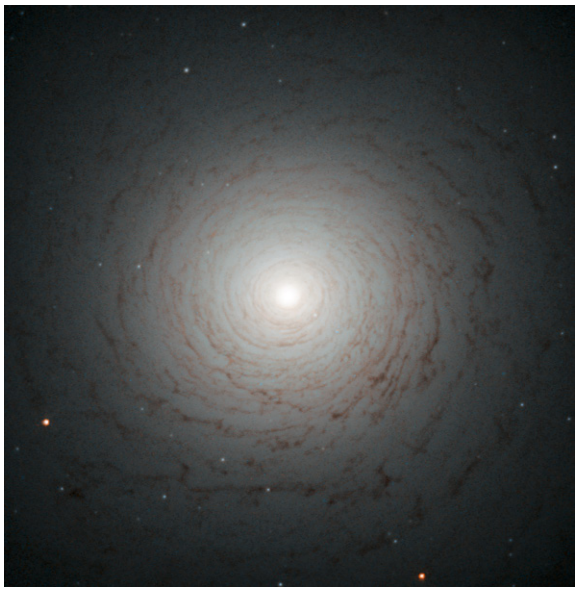
85. Hubble's last look at ISON before perihelion

Here Hubble has taken its closest look at the innermost region of the ISON comet, where geysers of sublimating ice are fueling a spectacular tail.

Made from observations on November 2, 2013, the round coma around ISON's nucleus is blue and the tail has a redder hue. Ice and gas in the coma reflect blue light from the Sun, while dust grains in the tail reflect more red light than blue light. This is the most colour separation seen so far in ISON and the comet, nearer than ever to the Sun, is brighter and more structured than ever before.

Comet ISON came closest to the Sun on November 28, a point in its orbit known as perihelion. Comet ISON was fairly quiet until November 1, when it experienced an outburst that doubled the amount of gas the comet emitted. After this image was taken, a second outburst shook the comet, increasing its activity by a factor of ten.

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



86. Mysterious old spiral

This striking cosmic whirl is the centre of galaxy NGC 524, located in the constellation of Pisces, some 90 million light-years from Earth.

NGC 524 is a lenticular galaxy. Lenticular galaxies are believed to be an intermediate state in galactic evolution — they are neither elliptical nor spiral. Spirals are middle-aged galaxies with vast, pinwheeling arms that contain millions of stars. Along with these stars are large clouds of gas and dust that, when dense enough, are the nurseries where new stars are born. When all the gas is either depleted or lost into space, the arms gradually fade away and the spiral shape begins to weaken. At the end of this process, what remains is a lenticular galaxy — a bright disc full of old, red stars surrounded by what little gas and dust the galaxy has managed to cling on to.

This image shows the shape of NGC 524 in detail, formed by the remaining gas surrounding the galaxy's central bulge. Observations of this galaxy have revealed that it maintains some spiral-like motion, explaining its intricate structure.

Credit: ESA/Hubble & NASA

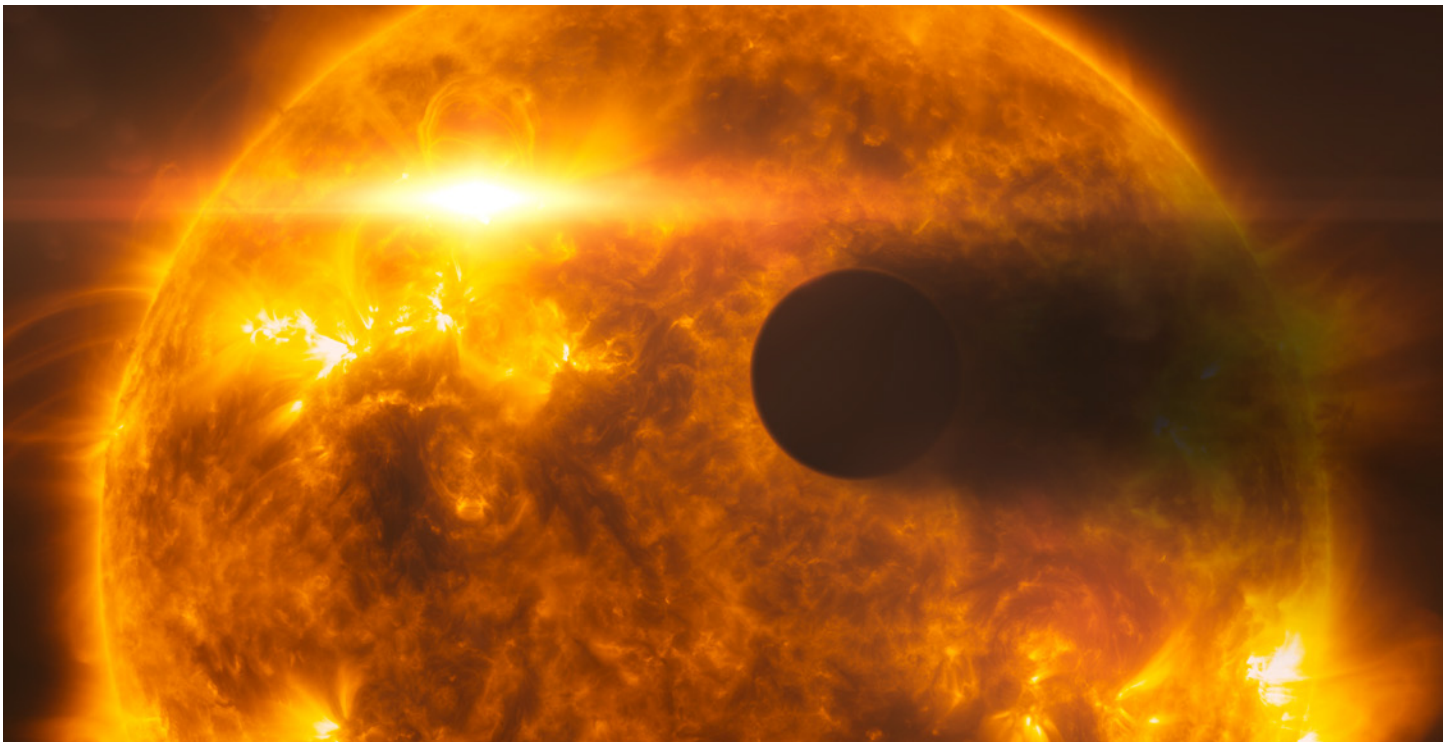
87 Stellar flare hits HD 189733b

(artist's impression)

This artist's impression shows exoplanet HD 189733b, as it passes in front of its parent star, called HD 189733A. Hubble's instruments observed the system in 2010, and in 2011 following a large flare from the star (depicted in the image). Following the flare, Hubble observed the planet's atmosphere evaporating at a rate of over 1000 tonnes per second.

In this picture, the surface of the star, which is around 80% the mass of the Sun, is based on observations of the Sun from the Solar Dynamics Observatory.

Credit: NASA, ESA, L. Calçada



"I study the atmospheres of planets orbiting nearby stars (also known as exoplanets), and it's safe to say that this field is completely dominated by space telescopes, including both Hubble and Spitzer.

"Thirteen years ago Hubble was the first telescope to detect the atmosphere of an extrasolar planet, and today we are using the same techniques to study the atmospheres of an entirely new class of planets known as 'super-Earths.' These worlds have masses between 1-10 times that of the Earth and compositions ranging from dense rock to puffy, hydrogen- or water-rich 'mini-Neptunes'. They are the most common kind of extrasolar planet found in our surveys of nearby stars, yet we don't have one in our own solar system. By studying the atmospheres of these planets we can gain important clues that will help us to understand their mysterious origins."

— Dr. Heather Knutson

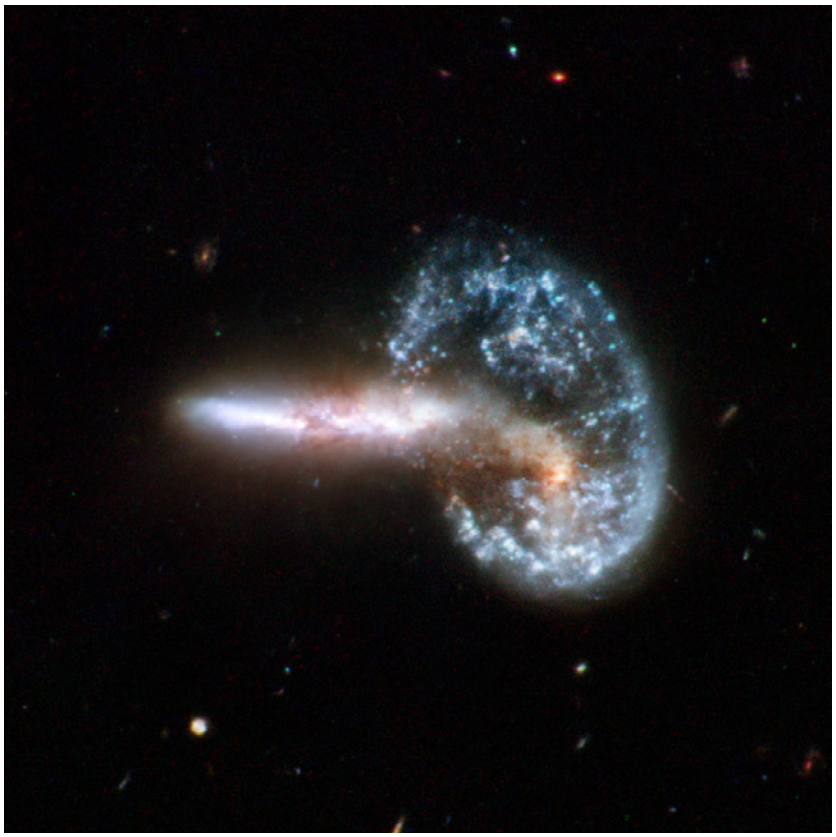
Assistant Professor of Planetary Science
California Institute of Technology

88. Arp 148

Arp 148 is the staggering aftermath of an encounter between two galaxies, resulting in a ring-shaped galaxy and a long-tailed companion. The collision between the two parent galaxies produced a shockwave effect that first drew matter into the centre and then caused it to propagate outwards in a ring. The elongated companion perpendicular to the ring suggests that Arp 148 is a unique snapshot of an ongoing collision. Infrared observations reveal a strong obscuration region that appears as a dark dust lane across the nucleus in optical light.

This image is part of a large collection of 59 images of merging galaxies taken by the Hubble Space Telescope and released on the occasion of its 18th anniversary on 24th April 2008.

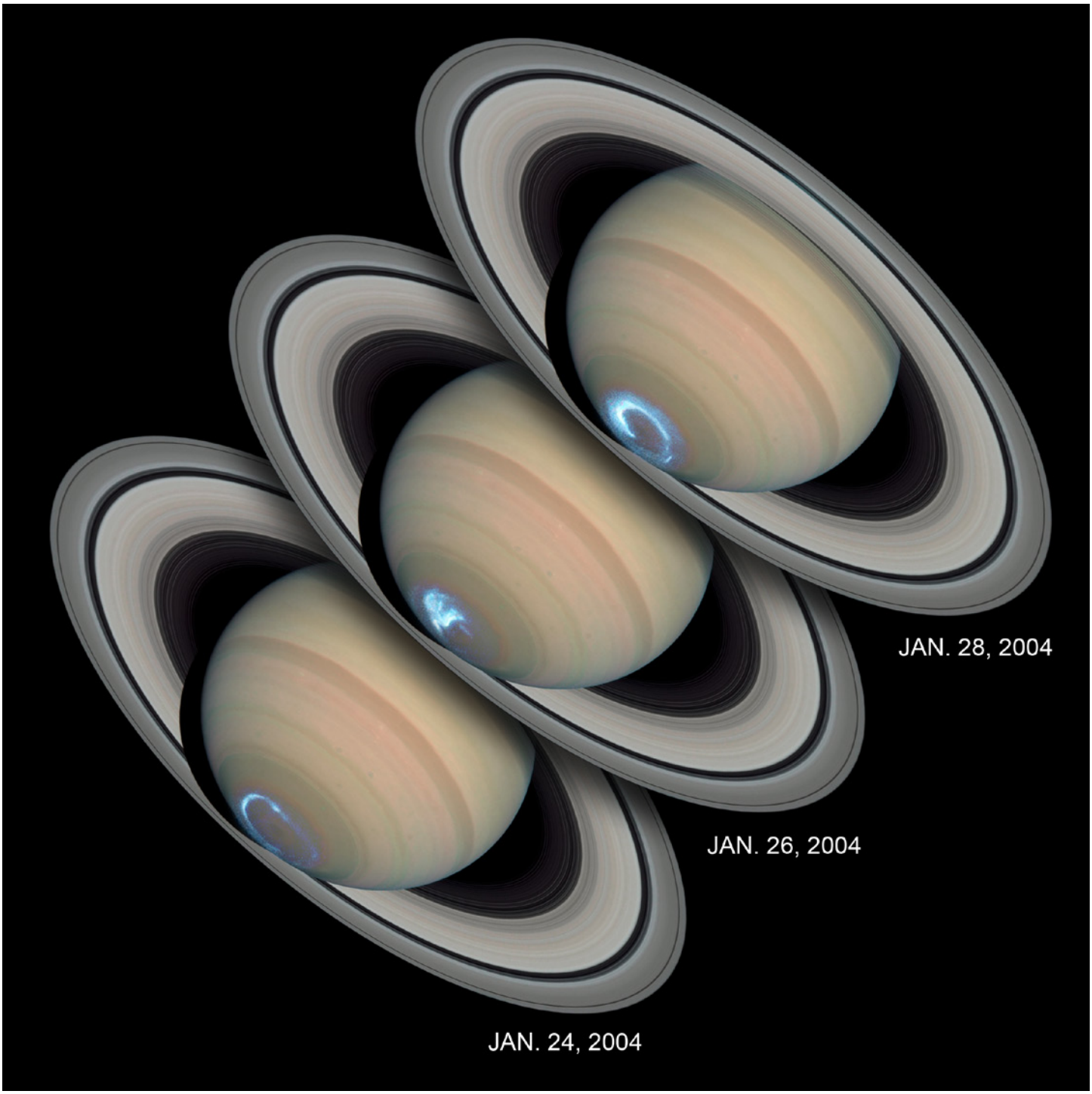
Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University), K. Noll (STScI), and J. Westphal (Caltech)



89. Stellar fireworks ablaze in NGC 4449

Hundreds of thousands of vibrant blue and red stars are visible in this image of galaxy NGC 4449. Hot bluish white clusters of massive stars are scattered throughout the galaxy, interspersed with numerous dustier reddish regions of current star formation. Massive dark clouds of gas and dust are silhouetted against the flaming starlight.

Credit: NASA, ESA, A. Aloisi (STScI/ESA), and The Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration


JAN. 28, 2004
JAN. 26, 2004
JAN. 24, 2004

20. Saturn's dynamic aurorae

These images reveal the dynamic nature of Saturn's aurorae. Viewing the planet's southern polar region for several days, Hubble snapped a series of photographs of the aurora dancing in the sky. The snapshots show that Saturn's aurorae differ in character from day to day, as they do on Earth, moving around on some days and remaining stationary on others. But compared with Earth, where auroral storms develop in about 10 minutes and may last for a few hours, Saturn's auroral displays always appear bright and may last for several days.

The observations, made by Hubble and the Cassini spacecraft, while en route to the planet, suggest that Saturn's auroral storms are driven mainly by the pressure of the solar wind - a stream of charged particles from the Sun - rather than by the Sun's magnetic field.

The aurora's strong brightening on Jan. 28, 2004 corresponds with the recent arrival of a large disturbance in the solar wind. The image shows that when Saturn's auroras become brighter (and thus more powerful), the ring of light encircling the pole shrinks in diameter.

Seen from space, an aurora appears as a ring of glowing gases circling a planet's polar region. Auroral displays are initiated when charged particles in space collide with a planet's magnetic field. The charged particles are accelerated to high energies and stream into the upper atmosphere. Collisions with the gases in the planet's atmosphere produce flashes of glowing energy in the form of visible, ultraviolet, and infrared light.

Astronomers combined ultraviolet images of Saturn's southern polar region with visible-light images of the planet and its rings to make this picture. The auroral display appears blue because of the glow of ultraviolet light. In reality, the aurora would appear red to an observer at Saturn because of the presence of glowing hydrogen in the atmosphere. On Earth, charged particles from the Sun collide with nitrogen and oxygen in the upper atmosphere, creating auroral displays colored mostly green and blue.

The ultraviolet images were taken on Jan. 24, 26, and 28, 2004 by Hubble's Space Telescope Imaging Spectrograph. Erich Karkoschka of the University of Arizona, USA used the telescope's Advanced Camera for Surveys on March 22, 2004 to take the visible-light images.

Credit: NASA, ESA, J. Clarke (Boston University, USA), and Z. Levay (STScI)

"Hubble has been a pivotal observatory in my work. One of my first projects involved processing early images from before Hubble's corrective optics were installed, and I have been involved in observing the outer planets ever since.

"Hubble images have been used in most of my scientific projects, and have provided a long-term record of the atmospheres of those planets. Given the very long orbits in the outer solar system, having a record over decades is critical to understanding their atmospheric processes."

— Dr. Amy A. Simon

Senior Scientist for Planetary Atmospheres
NASA Goddard Space Flight Center
Greenbelt, Maryland

94. New view of the Helix Nebula

This composite image is a view of the colorful Helix Nebula taken with the Advanced Camera for Surveys aboard the Hubble Space Telescope and the Mosaic II Camera on the 4-meter telescope at Cerro Tololo Inter-American Observatory in Chile. The object is so large that both telescopes were needed to capture a complete view. The Helix is a planetary nebula, the glowing gaseous envelope expelled by a dying, sun-like star. The Helix resembles a simple doughnut as seen from Earth. But looks can be deceiving. New evidence suggests that the Helix consists of two gaseous disks nearly perpendicular to each other.

Credit: NASA, ESA, C.R. O'Dell (Vanderbilt University), and M. Meixner, P. McCullough, and G. Bacon (Space Telescope Science Institute)

Hubble's top discoveries "is a very personal list:

"1) The accelerating universe, kind of a no-brainer there, we think most people would agree with that. The Nobel committee thought so, too.

"2) Accurate determination of the Hubble constant, the current rate at which the universe is expanding. Prior to Hubble the telescope, Hubble the number wasn't known to better than a factor of two. It's now at ~10% accuracy.

"3) Discovery that every large galaxy has a supermassive black hole at its center. This one might not make everyone's list, but it's what we work on!"

— Dr. Bradley M. Peterson & Dr. Gisella De Rosa

Professor and Chair of Astronomy
Ohio State University
Columbus, Ohio

Visiting Astronomer
Space Telescope Science Institute
Baltimore, Maryland

92. 'Ghost Head Nebula'

The 'Ghost Head Nebula' is one of a chain of star-forming regions lying south of the 30 Doradus nebula in the Large Magellanic Cloud. Two bright regions (the 'eyes of the ghost'), named A1 (left) and A2 (right), are very hot, glowing 'blobs' of hydrogen and oxygen.

The bubble in A1 is produced by the hot, intense radiation and powerful stellar wind from a single massive star. A2 has a more complex appearance due to the presence of more dust, and it contains several hidden, massive stars.

The massive stars in A1 and A2 must have formed within the last 10 000 years since their natal gas shrouds are not yet disrupted by the powerful radiation of the newly born stars.

Credit: ESA, NASA, & Mohammad Heydari-Malayeri (Observatoire de Paris, France)

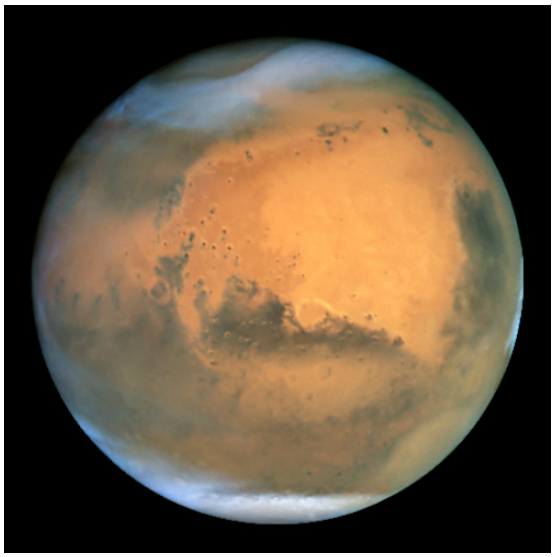
93. Best Earth-based view of Mars ever

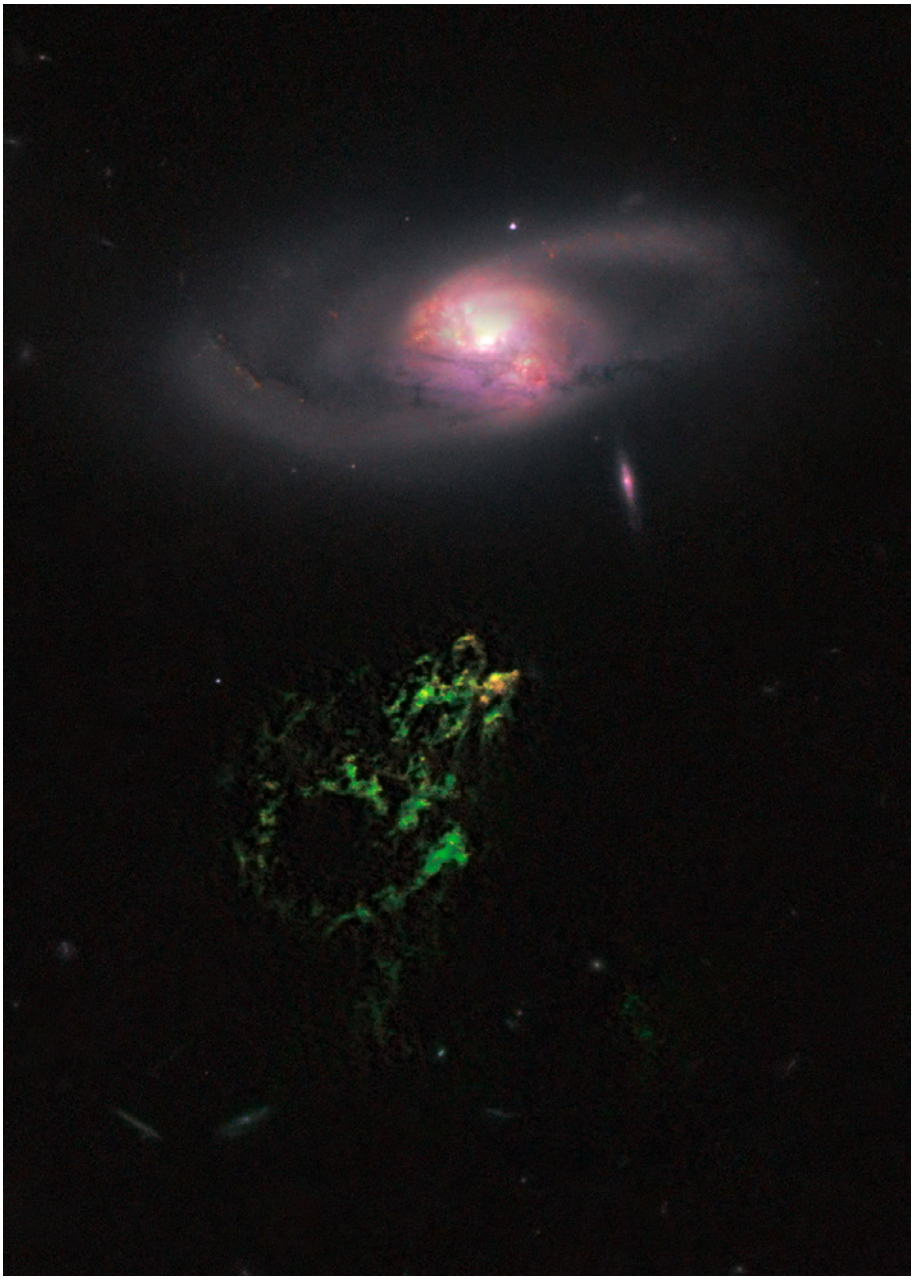
Frosty white water ice clouds and swirling orange dust storms above a vivid rusty landscape reveal Mars as a dynamic planet in this sharpest view ever obtained by an Earth-based telescope.

The Earth-orbiting Hubble telescope snapped this picture on June 26, when Mars was approximately 43 million miles (68 million km) from Earth - its closest approach to our planet since 1988. Hubble can see details as small as 10 miles (16 km) across.

Especially striking is the large amount of seasonal dust storm activity seen in this image. One large storm system is churning high above the northern polar cap [top of image], and a smaller dust storm cloud can be seen nearby. Another large duststorm is spilling out of the giant Hellas impact basin in the Southern Hemisphere [lower right].

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





94 A space oddity

In this image by the NASA/ESA Hubble Space Telescope, an unusual, ghostly green blob of gas appears to float near a normal-looking spiral galaxy.

The bizarre object, dubbed Hanny's Voorwerp (Hanny's Object in Dutch), is the only visible part of a streamer of gas stretching 300 000 light-years around the galaxy, called IC 2497. The greenish Voorwerp is visible because a searchlight beam of light from the galaxy's core has illuminated it. This beam came from a quasar, a bright, energetic object that is powered by a black hole. The quasar may have turned off in the last 200 000 years.

This Hubble view uncovers a pocket of star clusters, the yellowish-orange area at the tip of Hanny's Voorwerp. The star clusters are confined to an area that is a few thousand light-years wide. The youngest stars are a couple of million years old. The Voorwerp is the size of the Milky Way, and its bright green colour is from glowing oxygen.

Credit: NASA, ESA, William Keel (University of Alabama, Tuscaloosa), and the Galaxy Zoo team

95. All that glitters

This striking Hubble Space Telescope image shows a glittering bauble named Messier 92. Located in the northern constellation of Hercules, this globular cluster — a ball of stars that orbits a galactic core like a satellite — was first discovered by astronomer Johann Elert Bode in 1777.

Messier 92 is one of the brightest globular clusters in the Milky Way, and is visible to the naked eye under good observing conditions. It is very tightly packed with stars, containing some 330 000 stars in total. As is characteristic of globular clusters, the predominant elements within Messier 92 are hydrogen and helium, with only traces of others. It is actually what is known as an Oosterhoff type II (OoII) globular cluster, meaning that it belongs to a group of metal-poor clusters — to astronomers, metals are all elements heavier than hydrogen and helium.

By exploring the composition of globulars like Messier 92, astronomers can figure out how old these clusters are. As well as being bright, Messier 92 is also old, being one of the oldest star clusters in the Milky Way, with an age almost the same as the age of the Universe.

Credit: ESA/Hubble & NASA

"It is hard to say what Hubble's lasting scientific legacy will be, as I would imagine there are fundamental discoveries across the entire range of sub-fields within astronomy and physics.

"With regards to Hubble's legacy amongst society, the story of Hubble is a human one which can touch all of us. Hubble overcame adversity early on, from problems with the mirror optics to gyroscope and instrument failures.

"Despite all of these challenges, Hubble has proceeded to revolutionize our understanding of the cosmos. NASA believes that Hubble can get to 2020 and beyond, a lifetime that was likely inconceivable at launch.

"To me, Hubble's story tells us that with perseverance, we can far exceed our own expectations."

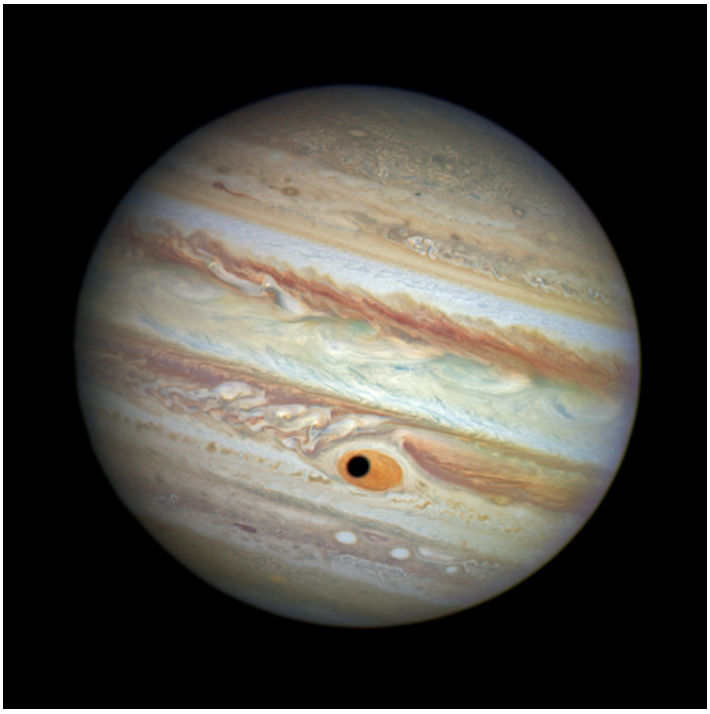
— Dr. Katherine E. Whitaker

NASA Postdoctoral Program Fellow
Goddard Space Flight Center
Greenbelt, Maryland

96. Jets, bubbles and bursts of light in Taurus

The Hubble Space Telescope has snapped a striking view of a multiple star system called XZ Tauri, its neighbour HL Tauri and several nearby young stellar objects. XZ Tauri is blowing a hot bubble of gas into the surrounding space, which is filled with bright and beautiful clumps that are emitting strong winds and jets. These objects illuminate the region, creating a truly dramatic scene.

Credit: ESA/Hubble and NASA



97. Jupiter's Red Spot and Ganymede's shadow

This Hubble image shows a gorgeous close-up view of the planet Jupiter.

Astronomers were using Hubble to monitor changes in Jupiter's immense Great Red Spot (GRS) storm. During the exposures, on 21 April 2014, the shadow of the Jovian moon Ganymede swept across the center of the GRS. Giving the giant planet the uncanny appearance of having a pupil in the center of a 16 000 kilometre wide eye.

Credit: NASA, ESA, and A. Simon (Goddard Space Flight Center)

28 Spiral in Serpens

This new NASA/ESA Hubble Space Telescope image shows a beautiful spiral galaxy known as PGC 54493, located in the constellation of Serpens (The Serpent). This galaxy is part of a galaxy cluster that has been studied by astronomers exploring an intriguing phenomenon known as weak gravitational lensing.

This effect, caused by the uneven distribution of matter (including dark matter) throughout the Universe, has been explored via surveys such as the Hubble Medium Deep Survey. Dark matter is one of the great mysteries in cosmology. It behaves very differently from ordinary matter as it does not emit or absorb light or other forms of electromagnetic energy — hence the term "dark".

Even though we cannot observe dark matter directly, we know it exists. One prominent piece of evidence for the existence of this mysterious matter is known as the "galaxy rotation problem". Galaxies rotate at such speeds and in such a way that ordinary matter alone — the stuff we see — would not be able to hold them together. The amount of mass that is "missing" visibly is dark matter, which is thought to make up some 27% of the total contents of the Universe, with dark energy and normal matter making up the rest. PGC 55493 has been studied in connection with an effect known as cosmic shearing. This is a weak gravitational lensing effect that creates tiny distortions in images of distant galaxies.

Credit: ESA/Hubble & NASA

"Hubble brought the Universe into our backyard. Or rather, it expanded our backyards to enclose the Universe itself. It did that with images so intellectually, visually, and even spiritually fulfilling that most don't even need captions."

— Neil deGrasse Tyson

Director of Hayden Planetarium
American Museum of Natural History
New York, New York

99. Light and dark

Surrounded by bright stars, towards the upper middle of the frame we see a small young stellar object (YSO) known as SSTC2D J033038.2+303212. Located in the constellation of Perseus, this star is in the early stages of its life and is still forming into a fully grown star. In this view it appears to have a murky chimney of material emanating outwards and downwards, framed by bright bursts of gas flowing from the star itself. This fledgling star is actually surrounded by a bright disc of material swirling around it as it forms — a disc that we see edge-on from our perspective.

However, this small bright speck is dwarfed by its cosmic neighbour towards the bottom of the frame, a clump of bright, wispy gas swirling around as it appears to spew dark material out into space. The bright cloud is a reflection nebula known as [B77] 63, a cloud of interstellar gas that is reflecting light from the stars embedded within it.

These stars are lighting up the surrounding gas and sculpting it into the wispy shape seen in this image. However, the most dramatic part of the image seems to be a dark stream of smoke piling outwards from [B77] 63 and its stars — a dark nebula called Dobashi 4173. Dark nebulae are incredibly dense clouds of pitch-dark material that obscure the patches of sky behind them.

Credit: ESA/Hubble & NASA

100. Stellar sneezing fit

Look at the bright star in the middle of this image. Achoo! It has just sneezed. This sight will only last for a few thousand years — a blink of an eye in the young star's life.

If you could carry on watching for a few years you would realise it's not just one sneeze, but a sneezing fit. This young star is firing off salvos of super-hot, super-fast gas before it finally exhausts itself. These bursts of gas have shaped the turbulent surroundings, creating structures known as Herbig-Haro objects.

These objects are formed from the star's energetic "sneezes". These salvos can contain as much mass as our home planet, and cannon into nearby clouds of gas at hundreds of kilometres per second. Shock waves form, such as the U-shape below this star. Unlike most other astronomical phenomena, as the waves crash outwards, they can be seen moving across human timescales. Soon, this star will stop sneezing, and grow up to be a star like the Sun.

Credit: ESA/Hubble & NASA

Edwin P. Hubble:
The man behind the name

When talking about the Hubble Space Telescope one man is often forgotten: That man who gave the space telescope its name: Edwin Powell Hubble. Today, most astronomers see him as the most important observational cosmologist in the 20th century and he played a crucial role in establishing the field of extragalactic astronomy.

As a result of Hubble's work, our perception of mankind's place in the Universe has changed forever: humans have once again been set aside from the centre of the Universe. When scientists decided to name the Space Telescope after the founder of modern cosmology the choice could not have been more appropriate.

Studio Portrait of Edwin Powell Hubble, dated 1931. Photographer: Johan Hagemeyer

A promising student

Edwin Hubble was born in Missouri in 1889, the son of an insurance executive, and moved to Chicago nine years later. At his high school graduation in 1906 he gained a scholarship for the University of Chicago where he finally obtained a degree in Mathematics and Astronomy in 1910.

The Rhodes scholar

A tall, powerfully built young man, Hubble loved basketball and boxing, and the combination of athletic prowess and academic ability earned him a Rhodes scholarship to Oxford. There, a promise made to his dying father, led him to study law rather than science, although he also took up Literature and Spanish.

He studied Roman and English Law at Oxford and returned to the United States only in 1913. Here he passed the bar examination and practised law half-heartedly for a year in Kentucky, where his family was then living.

The beloved high school teacher and coach

He was also hired by New Albany High School (New Albany, Indiana) in the autumn of 1913 to teach Spanish, Physics and Mathematics, and to coach basketball. His popularity as a teacher is recorded in the school yearbook dedicated to him: "To our beloved teacher of Spanish and Physics, who has been a loyal friend to us in our senior year, ever willing to cheer and help us both in school and on the field, we, the class of 1914, lovingly dedicate this book."

When the school term ended in May 1914, Hubble decided to pursue his first passion and so returned to university as a graduate student to study more astronomy.

War postpones Hubble's astronomical debut

Early in 1917, while still finishing the work for his doctorate, Hubble was invited by George Ellery Hale, founder of the Mount Wilson Observatory, in Pasadena, California, to join the staff there. This was a great opportunity, but it came in April of a dreadful year. After sitting up all night to finish his PhD thesis and taking the oral examination the next morning, Hubble enlisted in the infantry and telegraphed Hale: "Regret cannot accept your invitation. Am off to the war."

He served in France and next returned to the United States in 1919. He went immediately to the Mount Wilson Observatory, where the newly discharged Major Hubble, as he invariably introduced himself, arrived, still in uniform, but ready to start observing.

Hubble was lucky enough to be in the right place at the right time. Mount Wilson was the centre of observational work underpinning the new astrophysics, later called cosmology, and the 100- inch Hooker Telescope, then the most powerful on Earth, had just been completed and installed after nearly a decade of work.

On the mountain Hubble encountered his greatest scientific rival, Harlow Shapley, who had already made his reputation by measuring the size of the Milky Way, our own Galaxy. Shapley had used a method pioneered by Henrietta Leavitt at the Harvard College Observatory that relied on the behaviour of standardised light variations from bright stars called Cepheid variables to establish the distance of an object.

His result of 300 000 light-years for the width of the galaxy was roughly 10 times the previously accepted value. However Shapley, like most astronomers of the time, still thought that the Milky Way was all there was to

the Universe. Despite a suggestion first made by William Herschel in the 18th century, he shared the accepted view that all nebulae were relatively nearby objects and merely patches of dust and gas in the sky.

The turning point

Hubble had to spend many bitterly cold nights sitting at the powerful Hooker telescope before he could prove Shapley wrong. In October 1923 he spotted what he first thought was a nova star flaring up dramatically in the M31 "nebula" in the constellation of Andromeda. After careful examination of photographic plates of the same area taken previously by other astronomers, including Shapley, he realised that it was a Cepheid star. Hubble used Shapley's method to measure the distance to the new Cepheid. He could then place M31 a million light-years away - far outside the Milky Way and thus itself a galaxy containing millions of stars. The known Universe had expanded dramatically that day and – in a sense – the Cosmos itself had been discovered!

Just the beginning

This discovery was of great importance to the astronomical world, but Hubble's greatest moment was yet to come. He began to classify all the known nebulae and to measure their velocities from the spectra of their emitted light. In 1929 he made another startling find – all galaxies seemed to be receding from us with velocities that increased in proportion to their distance from us – a relationship now known as Hubble's Law.

This discovery was a tremendous breakthrough for the astronomy of that time as it overturned the conventional view of a static Universe and showed that the Universe itself was expanding. More than a decade earlier, Einstein himself had bowed to the observational wisdom of the day and corrected his equations, which had originally predicted an expanding Universe. Now Hubble had demonstrated that Einstein was right in the first place.

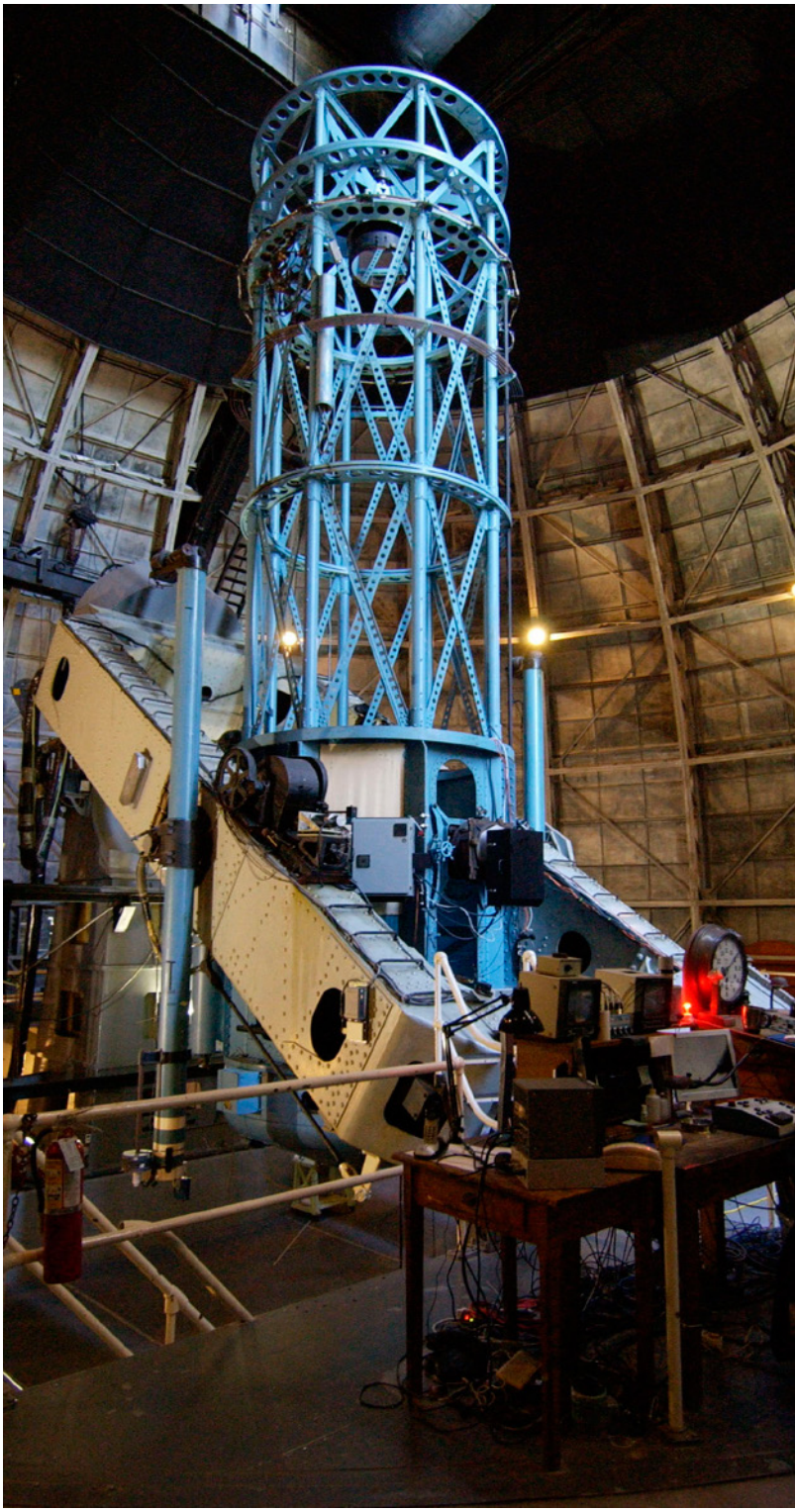
The now elderly, world-famous physicist went specially to visit Hubble at Mount Wilson to express his gratitude. He called the original change of his beloved equations "the greatest blunder of my life."

Another war stops Hubble again

Hubble worked on indefatigably at Mount Wilson until the summer of 1942, when he left to serve in World War II. He was awarded the Medal of Merit in 1946. Finally, he went back to his Observatory. His last great contribution to astronomy was a central role in the design and construction of the Hale 200-inch Telescope on Palomar Mountain. Four times as powerful as the Hooker, the Hale would be the largest telescope on Earth for decades. In 1949, he was honoured by being allowed the first use of the telescope.

No Nobel Prize for an astronomer

During his life, Hubble had tried to obtain the Nobel Prize, even hiring a publicity agent to promote his cause



The 100 inch (2.5 m) Hooker telescope at Mount Wilson Observatory near Los Angeles, California. This is the telescope that Edwin Hubble used to measure galaxy redshifts and discover the general expansion of the universe. Credit: Andrew Dunn

in the late 1940s, but all the effort was in vain as there was no category for astronomy. Hubble died in 1953 while preparing for several nights of observations, his last great ambition unfulfilled.

He would have been thrilled had he known that the Space Telescope is named after him, so that astronomers can continue to "hope to find something we had not expected", as he said in 1948 during a BBC broadcast in London.

How they do it:

The processing of Hubble images from B&W into stunning full-color

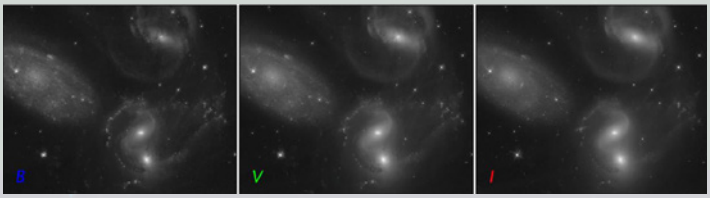
By Mike Barrett

Everyone has seen the dramatic images produced by the Hubble Telescope from the iconic Pillars of Creation to the hundreds of galaxies in one shot, but how are these images created?

The Hubble Telescope captures images in monochrome, just like the old black and white photographs with no color, but the images we see are stunning vibrant color pictures. How are these created and what elements determine the color mapping?

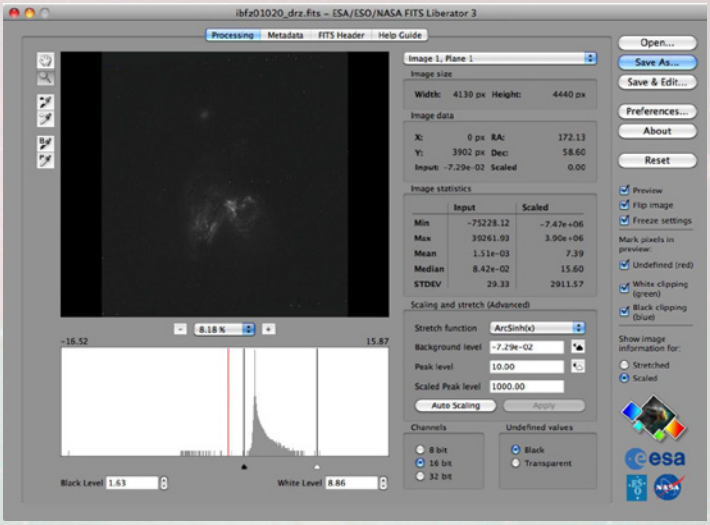
To understand the elements that create the images we need to understand what we see as an image. A typical image is created from a grid of pixels or dots. Each pixel represents a colour and intensity in the image. These are grouped together so tightly that the eye cannot see the individual pixel, but sees a smooth transition from one pixel to the next.

Basically a color image is created from three separate components: Red; Green; and Blue. From these prime colours any other color can be represented by mixing them in varying proportions. Each pixel of the image has 3 components Red, Green and Blue with a scale of 0 to 32,768 representing the intensity of the color for that pixel. In this case 0 represents no colour and 32,768 is full color. So a pixel having an RGB value of 0:0:0 is black and that having 32,768:32,768:32,768 will be white.



HST WFC3/UVIS images of the galaxy group Stephan's Quintet in three broad-band visible-light filters; left: F439W (B), center: F555W (V) and right: F814W (I). Credit: STScI, OPO, Zolt Levay

Knowing how an image is constructed allows us to start to understand how a Hubble image is put together. Hubble has a number of instruments on the telescope, but the one we shall examine in this article is what is known as the Wide Field Camera 3 or WFC3. The camera of WFC3 is capable of recording a much larger spectrum than the human eye can see. This ranges from ultraviolet through visible light to near-infrared. The WFC3 camera is a 16 mega-pixel monochrome camera which produces a greyscale image. If an unfiltered image is taken it will include all the spectrum from ultraviolet to near infrared with each pixel having an intensity value of 0 to 32,768 representing the sum of all the light entering the camera. As this is greyscale there is just a single value for each pixel representing the intensity of the data recorded.



Screen image of the FITS Liberator GUI specially developed by the ESA and NASA for processing Hubble's images. Credit: STScI, OPO, Zolt Levay

Capturing the entire spectrum is not particularly useful and the image needs to be restricted to certain wavelengths of light. To restrict the type of data recorded by the camera there are a series of filters that can be placed in front of the camera's sensor to restrict the data recorded to particular wavelengths. To create a true colour image the camera must take 3 images: one only allowing red to pass through; one recording only the green light; and one the blue. These will all be monochrome images, but can be reconstructed into a normal color image.

Allowing a wide range of the spectrum to pass through a filter is known as Broadband filtering. A process that amateur astronomers use to eliminate the effects of light pollution is known as narrowband filtering. This allows astrophotography to be carried out even from city centres where the effects of the sodium lighting are filtered out allowing other light to pass through.

This is a fundamental principle for narrowband imaging and is based around spectrometry. Spectrometry is the ability to determine the composition of certain elements based on the light that is produced. This is of particular use to astronomy as it allows the study of particular gasses in the universe. Filters have been developed to isolate the more useful elements and can be used for imaging. In particular most emission nebula mainly consist of hydrogen and a hydrogen alpha can be used to restrict only light of the 656 nm wavelength to pass through.

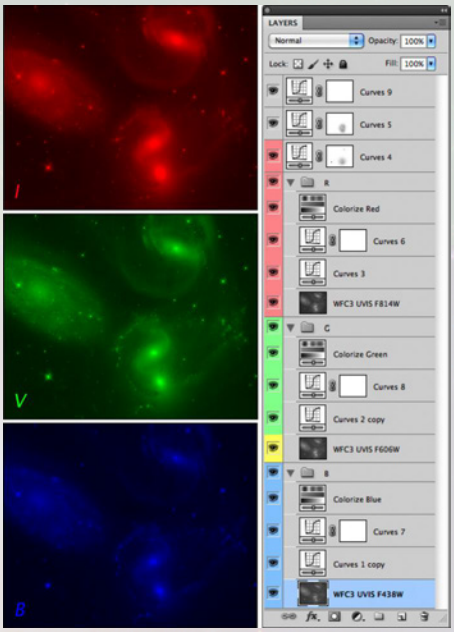
This principle of only letting certain wavelengths of the spectrum to reach the camera also applies to non-visible light such as ultraviolet at the blue end of the spectrum and infrared at the red end. The camera is able to see and record these wavelengths as differing intensities in

monochrome. This means that we now have a visual representation of data in the non-visible parts of the spectrum. Ultraviolet is particularly important as this is the hot areas where new stars are being created and represents new light. Infrared at the other end of the scale represents much older light and is associated with dying stars. Being able to study this data in addition to the visible light is important to gain a better understanding of what is happening in the universe.

This then raises an issue of how to represent the light that would normally be invisible to the human eye. This was solved by the creation of the "Hubble Palette" where the invisible light is mapped to a visible prime color i.e. the ultraiolet is the blue component, the infrared the red component etc. This has been extended to amateur astronomers who map narrowband images to color components thereby creating the false color Hubble Palette images.

With the theory out of the way we now need to get some good clean images with minimal noise and good light data. The light that is being collected is often very faint and almost indistinguishable from the dark background. So a method of capturing images and increasing the light data whilst minimising the noise is employed.

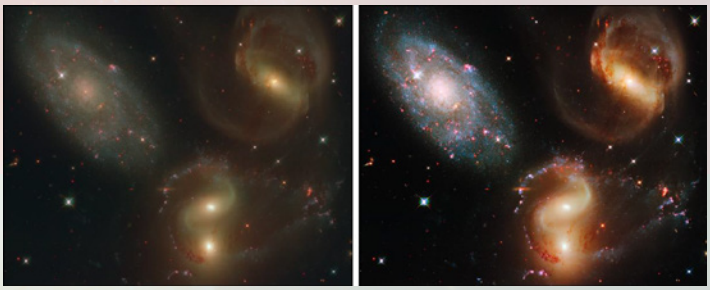
The capturing the light images is very similar to the way astrophotographers capture images on the ground. The telescope takes a number of images then stacks them together. One of the reasons this has to be done on the ground is to remove artefacts such as plane trails and satellite trails. Up on orbit the Hubble telescope is flying higher than any plane so why would this stacking need to take place? Well there may not be planes to contend with, but there are still satellites flying in higher orbits and also cosmic rays which will be captured by the camera.



Photoshop layers palette representing separate image layers for each filter dataset as the first set of images, as well as adjustment layers to change the brightness profile for each layer and apply hue to each filter layer. Additional curves adjustments apply to the composited image. Credit: STScI, OPO, Zolt Levay

Stacking images has two effects. Firstly it removes all cosmic rays, satellite trails and other transient, unwanted data. This is done in a software application which effectively looks at two images and compares one to another. If a pixel is set in one and not in the other then it is likely to be an artefact that needs to be removed. Secondly the more images that are combined together the more the data signal is enhanced whilst reducing the random background noise. The result of this process is an image that is clean, of good light quality and lower noise. This process has to be repeated for each different wavelength (filter) that will be incorporated into the final image.

The stacked images are then ready for processing into the final images. This is done by ensuring that all the components are of the same size and orientation with all the stars lining up as the images are layered on top of each other. This must be done prior to processing the images as they must all be in perfect alignment for the color components to be able to be merged into the final image.



Initial color composite from HST WFC3 images of Stephan's Quintet (left) rendered in hues assigned to datasets from several separate filters. The same image is adjusted (right) to improve the contrast, tonal range, and color. Credit: STScI, OPO, Zolt Levay

Once aligned the images are imported into a graphics processing package such as Adobe Photoshop. They are assigned layers within a single image. You can think of this process as placing three different transparent images on tracing paper and then shining a light behind it to project the combined image. This now is when each different layer is associated with a color enabling the combined image to be rendered as a full color image. The image is then modified with various transition tools to lighten and increase contrast both to the individual layers and the image overall. This will ultimately produce the final image.

If the layers that were combined were taken with red, green, and blue filters then the final image will be a true lifelike color image. If on the other hand the layers represent narrowband image data then the color mapping will produce a false color image. This is where the famous Hubble Palette is derived from. The Hubble Palette normally has the Hydrogen Alpha data mapped as green, the Sulphur II data mapped as red and the Oxygen III data assigned to blue. This color mapping produces the dramatic false color images that we are all used to seeing from the Hubble Telescope.

This is a rather simplistic explanation of the process, and there are many other steps that are allied to the data to produce the final images. The main interesting thought though is that the processing of data from the Hubble Telescope is very similar to that that amateur astronomers use from Earth based telescopes. NASA make the data from the Hubble Telescope available to the public and it is possible to create your own Hubble images by combining and processing the data. This will be the topic of a future article.

S.T.E.M. for the Classroom

Hubble, bubble, toil and trouble

Vocabulary

- **Focal Length:** The distance between a curved mirror and its Focal Point
- **Focal Point:** The position where all reflected light inside the telescope focuses to a point of light
- **Focal Surface:** The place where the Focal Point converges to
- **Primary Mirror:** The larger of the two curved mirrors that reflect the incoming light to the Secondary Mirror
- **Secondary Mirror:** The smaller of the two curved mirrors that direct reflected light from the Primary Mirror to the Focal Surface

Narrative

The Hubble Space Telescope (HST) is celebrating its 25th year in space. Launched in 1990, the HST fit snugly within the confines of the Space Shuttle's Payload Bay, which had a length of 18 meters, or almost 60 feet. The HST overcame its initial flaws and went on to become a historic telescope, thanks to the intrepid high–flying Shuttle repair crews and the folks on the ground. Indeed, after the fixes, the effective Focal Length of the HST lived up to its design of a whopping 57.6 meters (189 feet)!

Wait. The Space Shuttle Payload Bay was 18 m long, and the HST has a focal length of almost 58 m long. That's greater than the entire length of the Shuttle itself at 37 m (122 ft)! So how did the HST fit inside the Space Shuttle?

Enter the Cassegrain Telescope, a design that allows for a magnification factor! The HST is a Ritchey–Chrétien variant, which uses hyperbolic mirrors. A hole in the center of the Primary Mirror (M_1)allows the reflected light from the smaller Secondary Mirror (M_2)to pass through to the Focal Surface (F) located behind the Primary Mirror.

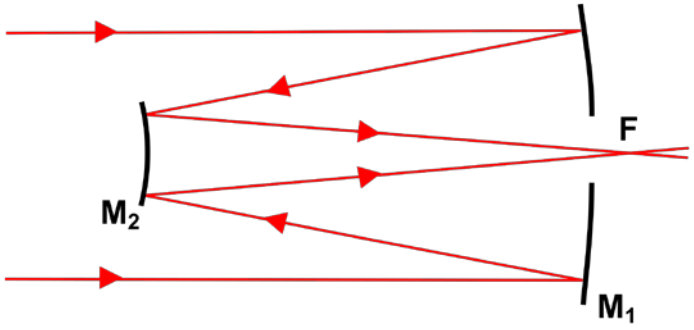
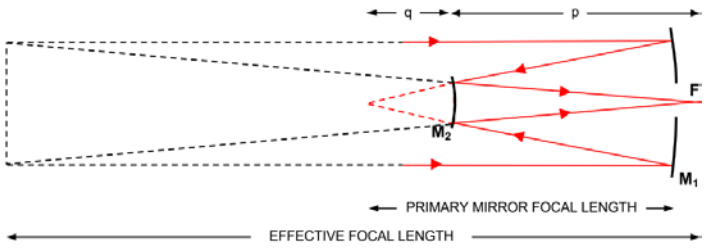


Diagram of a Cassegrain telescope which uses two reflecting mirrors. Credit: http://en.wikipedia.org/wiki/File:Diagram_Reflector_RitcheyChretien.svg

For a more in-depth treatment of this high school project by Joe Maness & Rich Holtzin visit www.stemfortheclassroom.com.

By extending the lines made from the reflected light bouncing off of M_2 backwards,we can see how this magnification effect works:



The M_2 mirror simply shortens the time needed to get to position F, the Focal Surface. The Effective Focal Length of a Cassegrain telescope (eFt) is:

eFt = Fp * q / p where,

Fp = Primary Mirror (M1)Focal Length

p = the system Focal Point (F) to Secondary Mirror (M_2) distance

q = the M_2 surface to the focal point of the M_1mirror distance

So let's check those Effective Focal Length figures, shall we?

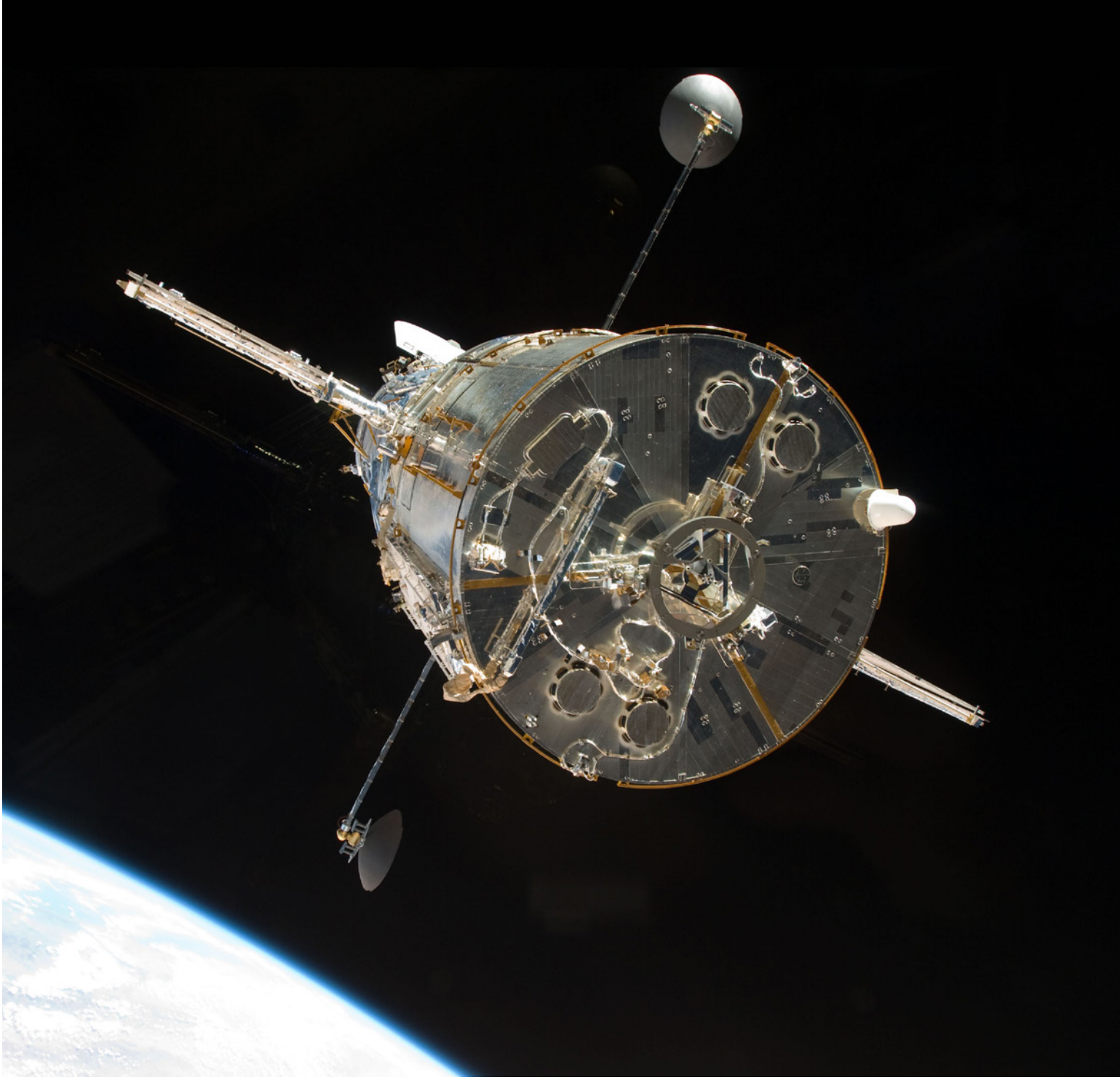
Example

Looking up the specifications of the HST, we find that the Focal Length of the Primary Mirror (Fp) is 5.52 m, the mirrors are separated by a distance (Md) of 4.91 m, and the Focal Surface (F) is 1.5 m behind the Primary Mirror.

So,

q = Md + F

= 4.91 + 1.5 = 6.41 m



The Space Shuttle Atlantis moves away from Hubble after the telescope's release on May 19, 2009 concluded Servicing Mission 4. The Soft Capture Mechanism, a ring that a future robotic mission can grapple in order to de-orbit the telescope, is visible in the center. Credit: NASA

p = Fp – Md
= 5.52 – 4.91 = 0.61 m

Therefore,

eFt = Fp * q / p
= (5.52) (6.41) / (0.61) = 58.0 m

Conclusion

Our calculation of 58.0 m is very close to the published figure of 57.6 m. This means that we can indeed fit a telescope with a large Focal Length inside a smaller cylindrical length. Sometimes great things really do come in small packages!

This also means that the HST magnifies the Primary Mirror Focal Length by a factor of ten. Holy Hubble Constant, Batman! No wonder it can see so far.

Despite its rough start, the HST has certainly earned its place in history, not only through the efforts of teams of people acting as one to give us mind–altering images of the Universe, but also by the use of clever mirror reflection techniques that allowed us to reach back even further in time and space.

Happy 25th Anniversary, Hubble Space Telescope!

Making house calls to Hubble

Servicing Mission 1

STS-61 Endeavour • December 2-13, 1993

Servicing Mission 1, launched in December 1993, was the first opportunity to conduct planned maintenance on the telescope. In addition, new instruments were installed and the optics of the flaw in Hubble's primary mirror was corrected.

After Hubble's deployment in 1990, scientist realized that the telescope's primary mirror had a flaw called spherical aberration. The outer edge of the mirror was ground too flat by a depth of 2.2 microns (roughly equal to one-fiftieth the thickness of a human hair). This aberration resulted in images that were fuzzy because some of the light from the objects being studied was being scattered.

COSTAR (the Corrective Optics Space Telescope Axial Replacement) was developed as an effective means of countering the effects of the flawed shape of the mirror. COSTAR was a telephone booth-sized instrument which placed 5 pairs of corrective mirrors, some as small as a nickel coin, in front of the Faint Object Camera, the Faint Object Spectrograph and the Goddard High Resolution Spectrograph.

The new Wide Field Planetary Camera (WFPC2) significantly improved ultraviolet performance over WFPC1, the original instrument. In addition to having more advanced detectors and more stringent contamination control, it also incorporated built-in corrective optics.

In addition, SM1 included the installation and replacement of other components including the solar arrays, Solar Array Drive Electronics (SADE), magnetometers, coprocessors for the flight computer, two rate sensor units, two gyroscope electronic control units, and GHRS redundancy kit.

Astronaut Story Musgrave (top right center) works with a restraint device near the Hubble Space Telescope during the first of five STS-61 EVAs. Fellow NASA astronaut Jeffrey Hoffman is seen at the bottom of the frame preparing to work with fuse plugs. Credit: NASA

Gregory Harbaugh (solid stripe on EMU) uses the remote manipulator system (RMS) as a cherry-picker device to service Hubble. In cooperation with Joseph Tanner, nearby, Harbaugh is in the process of replacing the Magnetic Sensing System (MSS) protective caps with new, permanent covers. Credit: NASA

Servicing Mission 2

STS-82 Discovery • February 11-21, 1997

The Second Servicing Mission, launched February 11, 1997, greatly improved Hubble's productivity. The installation of new instruments extended Hubble's wavelength range into the near infrared for imaging and spectroscopy, allowing us to probe the most distant reaches of the universe. The replacement of failed or degraded components increased efficiency and performance.

New Science Instruments

The Space Telescope Imaging Spectrograph (STIS) provides Hubble with unique and powerful spectroscopic capabilities. A spectrograph separates the light gathered by the telescope into its spectral components so that the composition, temperature, motion, and other chemical and physical properties can be analyzed.

STIS's two-dimensional detectors have allowed the instrument to gather 30 times more spectral data and 500 times more spatial data than the previous spectrographs.

One of the greatest advantages to using STIS is in the study of supermassive black holes. STIS searches for massive black holes by studying the star and gas dynamics around galactic centers. It measures the distribution of matter in the universe by studying quasar absorption lines. It also uses its high sensitivity and spatial resolution to study star formation in distant galaxies and perform spectroscopic mapping of solar system objects.

The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) has let us gain valuable new information on the dusty centers of galaxies and the formation of stars and planets. NICMOS consists of three cameras. It is capable of both infrared imaging and spectroscopic observations of astronomical targets.

NICMOS gave astronomers their first clear view of the universe at near-infrared wavelengths between 0.8 and 2.5 micrometers - longer wavelengths than the human eye can see. (The expansion of the universe shifts the light from very distant objects toward longer red and infrared wavelengths.) NICMOS's near infrared capabilities have provided views of objects too distant for research by previous optical and ultraviolet instruments.

Primary Spacecraft Hardware replacements

A refurbished Fine Guidance Sensor (FGS) was installed. Hubble uses this optical sensor provide pointing information for the spacecraft and as a scientific instrument for astrometric science. The modification to this FGS spare added the capability for ground-controlled alignment corrections.

The addition of an Optical Control Electronics Enhancement Kit. The OCE-EK provided the electronic pathway for commanding the alignment mechanisms.

The Solid State Recorder (SSR) replaced one of Hubble's three Engineering Science Tape Recorders (ESTR). The SSR provides much more flexibility than an ESTR, which is a reel-to-reel recorder and can store ten times more data. One of the other ESTRs was also replaced, but with a spare ESTR unit. During SM3A mission the reel-to-reel units were replaced with solid state recorders.

One of Hubble's four Reaction Wheel Assemblies was replaced by a refurbished spare. The RWA is part of Hubble's Pointing Control System. Spin momentum in the wheels moves the telescope to a target and maintains it in a stable position.

Secondary Spacecraft Hardware

Four Data Interface Units (DIU) on Hubble provide command and data interfaces between the spacecraft's data management system and the other HST subsystems. DIU-2 was replaced with a spare unit that has been modified and upgraded to correct for failures that occurred in the original unit.

The Solar Array Drive Electronics (SADE) controls the positioning of the solar arrays. Hubble has two SADEs of which one was replaced during the first servicing mission. The unit that was returned from orbit has been refurbished to correct for problems that resulted in transistor failures and was used to replace the second unit.

Payload Commander Steven L. Smith (bottom), and Mission Specialist John M. Grunsfeld, perform servicing tasks on the temporarily-captured Hubble Space Telescope. Grunsfeld is on a foot restraint connected to Discovery's RMS robot arm. Smith, making his second servicing visit to HST, is using handrails on the telescope. Credit: NASA

Servicing Mission 3A

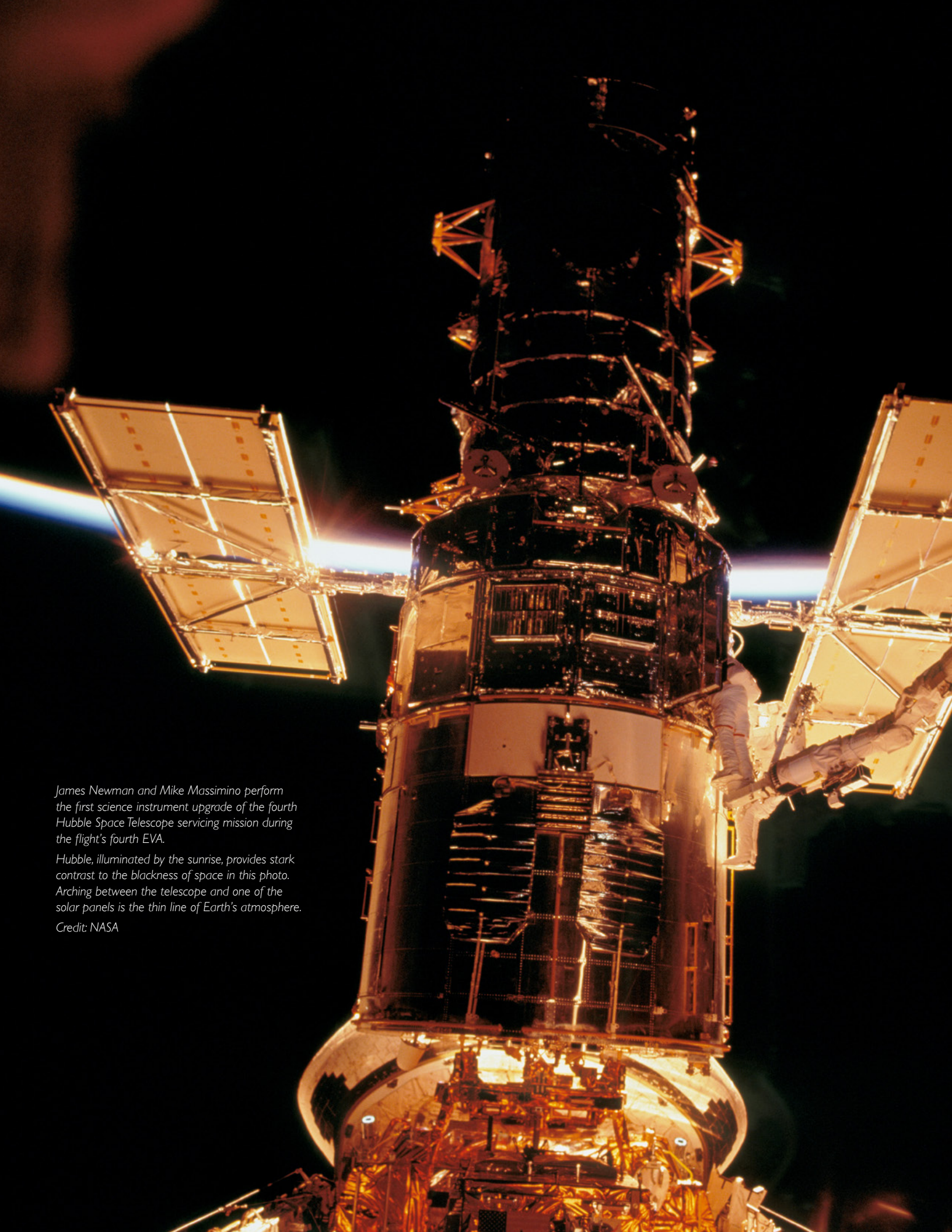
STS-103 Discovery • December 19-27, 1999

The Hubble Space Telescope is alive and well and back on duty after a successful servicing mission in December 1999. (SM3A). To prove it, NASA released two stunning images taken by Hubble just two weeks after Discovery's Christmas-time service call. Discovery's seven-member crew included two Hubble Servicing Mission veterans.

Launch of STS-103 What was originally conceived as a mission of preventive maintenance turned more urgent on November 13, 1999, when the fourth of six gyros failed and Hubble temporarily closed its eyes on the universe. Unable to conduct science without three working gyros, Hubble entered a state of dormancy called safe mode. Essentially, Hubble "went to sleep" while it waited for help.

NASA decided to split the Third Servicing Mission (SM3) into two parts, SM3A and SM3B, after the third of Hubble's six gyroscopes failed. In accordance with NASA's flight rules, a "call-up" mission was quickly approved and developed and executed in a record seven months.

Release of Hubble back into orbit The Hubble team has left the telescope far more fit and capable than ever before. The new, improved, and upgraded equipment included six fresh gyroscopes, six battery voltage/temperature improvement kits, a faster, more powerful, main computer, a next-generation solid state data recorder, a new transmitter, an enhanced fine guidance sensor, and new insulation.



James Newman and Mike Massimino perform the first science instrument upgrade of the fourth Hubble Space Telescope servicing mission during the flight's fourth EVA.

Hubble, illuminated by the sunrise, provides stark contrast to the blackness of space in this photo. Arching between the telescope and one of the solar panels is the thin line of Earth's atmosphere.

Credit: NASA

Servicing Mission 3B

STS-109 Columbia • March 1-12, 2002

Servicing Mission 3B was actually the fourth visit to Hubble. NASA split the original Servicing Mission 3 into two parts and conducted 3A in December of 1999. During SM3B a new science instrument was installed: the Advanced Camera for Surveys (ACS). Several other activities were accomplished as well over a 12-day mission with five spacewalks.

ACS Installation

With its wide field of view, superb image quality, and exquisite sensitivity, Hubble's newest science instrument, the Advanced Camera for Surveys (ACS) has 10 times more discovery power than the camera it replaces. In other words, ACS can produce 10 times as many science results in the same amount of time.

ASC sees in wavelengths ranging from visible to far ultraviolet. It is actually a team of three different cameras with specialized capabilities. The high resolution camera will take extremely detailed pictures of the inner regions of galaxies and search neighboring stars for planets and planets-to-be. The solar blind camera blocks visible light to enhance ultraviolet sensitivity. Among other things, it will be used to study weather on planets in our own solar system. With a field of view twice the size of Hubble's current surveyor, ACS's wide field camera will conduct new surveys of the universe. Astronomers will use it to study the nature and distribution of galaxies in order to understand how our universe evolved. (click for diagram of parts)

Solar Array 3 (SA3) Installation

Four large flexible solar array (SA) panels (wings) provide power to the observatory.

During SM1, the original arrays were replaced by SA2 and have powered Hubble for over eight years. Radiation and debris have taken their toll on sensitive electronics, which were replaced to ensure uninterrupted service for the remainder of the mission.

The new solar arrays (SA3) are rigid arrays, which do not roll up and therefore are more robust. Hubble got a brand new look with its latest set of solar wings. Although one-third smaller than the first two pairs, the power increase was between 20 and 30 percent. They are less susceptible to extreme temperatures and their smaller-sized will reduce the effects of atmospheric drag on the spacecraft.

Power Control Unit (PCU)

As Hubble's power switching station, the PCU controls and distributes electricity from the solar arrays and batteries to other parts of the telescope. Replacing the original PCU, which had been on the job for 11 years, required Hubble to be completely powered down for the first time since its launch in 1990. Hubble's new PCU has allowed astronomers to take full advantage of extra power generated by the new solar arrays.

NICMOS Cryocooler (NCC) Installation

Astronauts retrofitted an existing but dormant instrument called the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) with a new, experimental cooling system to return it to active duty. NICMOS was placed on Hubble in 1997 but became inactive two years later, after depleting the ice it needed to cool its infrared detectors. By fitting NICMOS with the experimental cryogenic system, NASA was able to re-cool the detectors to -334°F (-203°C or 70 K) to revive its infrared vision.

The super-quiet cooler uses ultra-high speed microturbines, the fastest of which spins at over 200,000 rpm (over 50 times the maximum speed of a typical car engine). Hubble's engineering team successfully demonstrated this technology in 1998 aboard STS-95 in the first on-orbit test of a high-performance, high-efficiency, mechanical cryocooler.

With a mostly dark home planet behind him, STS-125 mission specialist Michael Good rides Atlantis' remote manipulator system arm to where he needs be while working on the Hubble Space Telescope. Credit: NASA

STS-125 Mission:

Last visit to Hubble

By Andrew Green FBIS

For a mission that was almost never to be, STS-125 will be remembered in years to come as a resounding success story, one of NASA's great missions and a tribute to the ingenuity of engineers and astronauts alike. Rejuvenating the world's most famous telescope and setting it free to make more scientific discoveries the mission of STS-125 marked the final visit to the world's most famous telescope Hubble, and it took place in full view of the world's media.

I was fortunate to be at Kennedy Space Centre's, KSC press site for the duration of the flight, as a fellow of the British Interplanetary Society, reporting on behalf of the society I was honoured to be there.

In the past I have been fortunate to meet NASA Administrator Charles Bolden as well as Bruce McCandless, who were both members of the STS-31 team that launched Hubble into space in 1990, and I have met and lectured alongside Dr Jeffrey Hoffman who was mission specialist on STS-61 the first repair mission to Hubble in 1993, so I felt a close affinity with the mission of STS-125, I was so happy to be at the Kennedy Space Centre to witness it.

It seems such a long time ago now, way back on the 16th of January 2004, when the then NASA Administrator Sean O'Keefe originally cancelled the repair mission to Hubble, and by doing so, put paid to any future repair missions to the telescope as well. His reasons, citing safety constraints imposed by the Columbia Accident Investigation Board after the loss of Columbia on February 1, 2003.

During the announcement, Sean O'Keefe stated that it was his decision alone as administrator, and not a recommendation from any other departments. At the time, the decision was widely criticised by both the media and the scientific community and even some from within NASA. Hubble it seemed was to remain an injured bird with no hope of rescue.

At the time of Sean O'Keefe's decision, one senator in particular from Maryland, Barbara Mikulski who was actually a member of the Senate subcommittee that oversees NASA's budget, came out and openly accused him of making a decision outside the transparency process against the wishes of the science community. She was so annoyed that she actually stated she would work to reverse the decision that he had made.

In March of 2004, another representative, Mark Udall went one step further and actually introduced a bill to the House of Representatives that requested an independent panel of experts review Sean O'Keefe's decision to cancel the servicing mission in the first place.

Amazingly, at this time, someone else was joining Barbara Mikulski as an advocate for servicing Hubble; he was none other than NASA's Chief Scientist, John Grunsfeld who was to become one of the five STS-125 mission specialists. John

Posing for the STS-125 crew portrait, from left, are astronauts Michael J. Massimino, Michael T. Good, both mission specialists; Gregory C. Johnson, pilot; Scott D. Altman, commander; K. Megan McArthur, John M. Grunsfeld and Andrew J. Feustel, all mission specialists. The STS-125 mission was the final Space Shuttle mission to visit the Hubble Space Telescope for repairs and upgrades. Credit: NASA

Grunsfeld had also been present at that meeting when Sean O'Keefe announced the cancellation of all future Hubble repair missions. Grunsfeld had by that time, visited the telescope in orbit twice.

Though he was disappointed, Grunsfeld continued to spend time working on possible scenarios for the robotic repair missions to Hubble that had been suggested and other in-orbit repairs that did not include using humans. The National Academy of Sciences had also looked at robotic mission to service the telescope and had concluded that it was in no way a feasible option and in light of the scrutiny of the return to flight changes post Columbia they said a Hubble repair mission should be reassessed, that of course including humans.

When Sean O'Keefe announced his resignation as NASA Administrator in December 2004, members for the senate, the media and science community and those within NASA saw hope for the telescope's servicing mission to be reinstated.

Now that Michael Griffin had been appointed Sean O'Keefe's replacement, he literally took just two months to announce that he actually disagreed with Sean O'Keefe's decision, and that he would now consider sending a shuttle again to repair Hubble, maybe because he had close links to the telescope himself, given he was as an engineer and he had previously worked on Hubble's construction. He totally and utterly respected the discoveries the telescope brought to the science community and wider public audience as a whole.

When STS-114 the return to flight mission post Columbia was deemed a success and was then was then followed by STS 121 all the lessons learned and improvements in flight mission management, the managers and engineers started to work on a plan that would see a return to Hubble that would still adhere to the Columbia enquiry requirements.

On October 31, 2006, a major milestone was achieved, Michael Griffin finally announced that the Hubble servicing mission was reinstated and should be scheduled for 2008. He also announced the crew that would fly the mission, which included astronaut and physicist John Grunsfeld.

On finding out about the reinstated mission Senator Mikulski said "The Hubble telescope has been the greatest telescope since Galileo invented the first one. It has gone to look at places in the universe that we didn't know existed before" (We know it wasn't Galileo that invented the telescope, but we know what she meant)

Once the mission had been agreed it was then important to schedule the mission to fit in with the existing flight manifest. originally the STS-125 mission was assigned to space shuttle Discovery with a planned launch date sometime around May 2008 but delays to several space shuttle missions resulted in yet another change in mission ordering, and the orbiter assigned to STS-125 was eventually changed from Discovery to Atlantis.

Following tropical storm Fay in August 2008, Atlantis was rolled from one of the three Orbiter Processing Facility (OPF) to the huge behemoth that is the famous Vehicle Assembly Building (VAB), where it was mated to the external fuel tank (ET) and the solid rocket boosters (SRBs) some issues were then encountered during the stacking process, and more terrible weather due to Hurricane Hanna

caused yet another delay in the roll-out of Atlantis to the launch pad.

Even more delays followed when Lockheed Martin had problems with manufacturing delays on the External Tanks relating to enhancements imposed by the Columbia Accident Investigation Board which made it hard for them to produce two External Tanks, one required for Atlantis and another required for STS-400 Endeavour, the Hubble rescue mission.

Once these issued had been worked out though, it looked likely that all was set for STS-125 and a return to the Hubble Space Telescope, but an issue on Hubble itself rather than on the ground this time put paid to that. On September 27, 2008 aboard Hubble, the Science Instrument Command and Data Handling (SIC&DH) Unit on the Hubble Space Telescope failed. The unit is essential for Hubble as it keeps all science instrument systems aboard the telescope synchronized to process, format and temporarily store information on the data recorders or transmit science and engineering data to the ground. Without this working Hubble was unable to return data to the earth so mission planners decided yet again to delay the launch of STS-125.

On October 30, 2008, NASA announced that they had decided to remove Atlantis from its SRBs and ET stack and send it back yet again to the OPF to await a new targeted launch time which was then slated to be at at 1:11 p.m. EDT on May 12, 2009. On April 24, 2009, NASA managers issued a request to move the STS-125 launch up one day to May 11 at 2:01 p.m. EDT, in order to give them an added day's leeway before the range was passed to the the US Air Force for an exercise.

The mission would mark the 157th American manned space flight, the 126th shuttle mission. It would also be the 30th flight of Space Shuttle Atlantis.

Launch day

It was an early start, up at 4am, quick breakfast and heading out to the KSC Press Accreditation Office in order to get my mission badge that would allow me access to the media site at KSC for launch. On opening I was told told I had to go to the other KSC badging station to get a "Greeny" ID badge them return to the Press Accreditation Office for our mission badge, it was a learning curve but great experience too.

An STS-125 crewmember onboard Atlantis snapped a still photo of the Hubble Space Telescope following grapple of the giant observatory by the shuttle's Canadian-built remote manipulator system. Credit: NASA

All done I would now have to wait to be "bussed" into the press site along with Rick Mulheirn. All foreign media since 9/11 have to be bussed into the site each time they want to attend. Happily I waited and the bus duly arrived.

Up until this time I hadn't allowed myself to get too exited at the prospect of launch. I know many friends who have been to KSC over the years to see launches that have been scrubbed or cancelled; indeed, I met a gentleman in the airport who said this would be his 6th attempt, only ever seeing it go once, so it was always in my mind that something could go wrong.

The Space Shuttle is an incredible machine, but with so many complex flight systems and things that may go wrong, it seems you are in the lap of the gods but fortune was to smile on me this day.

Before launch there are a number of things that have to be done, the evening before launch day the crew spend their last night at the crew quarters building near the KSC industrial area as they prepare for the following day's events. The orbiter has undergone tests and fuelling as the countdown clock runs and then stops with its built in holds.

By this time, I was at the press site taking it all in, asking a few questions and talking to people about various things and introducing myself to some of the NASA people. I then go outside and put or camera gear by the side of the NASA TV stand in prime location for launch.

As I take a look around I notice that right by the side of me on NASA TV an interview is taking place. One one side is former astronaut Leroy Chiao (Ph.D.), in the middle conducting the interview is former CNN spaceflight correspondent Miles O'Brien and to my surprise on his right, non other than Sean O'Keefe, the very man who had cancelled Hubble's repair mission back in 2004. Here he is commenting on and watching the final mission to Hubble, quite an irony I thought.

I take a stroll and see retired astronaut Jim Newman a four-time shuttle flyer, who had visited Hubble as part of the STS-109 crew giving an interview. Lots of of power cables,

cameras, TV monitors, gazebos, TV and radio and TV vans and a myriad of different nationalities all here to see Atlantis soar skyward. I try to take all this in and enjoy being in such a privileged and famed place. It was as we were told busier than normal.

In the press room, we are told we will be allowed to go and see the crew "walkout" from their quarters, the busses are ready to take us there, but we have to leave all our gear on the floor beside the bus to begin with whilst the sniffer dogs make sure all is safe to go. Once at the crew building we get into position and after quite a wait we get to see the crew come out. You know of their impending arrival as just a few minutes before the suit techs in their distinctive Khaki overall's come out first with the crew's flight helmets in bags and then at the bottom of the elevator corridor a guy with what looked like an M16 rifle was spotted and soon after that you hear the distinctive sounds of the NASA "Huey" above your head as the crew make their way out to the awaiting press, other dignitaries and workers.

The crew give a wave then pause for a picture opportunity in front of the amassed press core, and then begin their boarding of the astro bus that will transport them out to Pad 39A. Several people commented that they didn't get too many good shots as the IMAX team had their camera in the way; a film is being made of the mission using IMAX so I look forward to seeing that sometime in the future. Fortunately for me though I was nowhere near it. It really was incredible to see the crew walking out; it's like being transported to a special place you only ever see on television, in magazines or books and where other historical astronauts have taken the very same steps.

The crew astro van is followed along by the NASA Huey and by an armoured vehicle , it looks very menacing and no doubt has enough armament inside it the size of a small country, but this is serious business and NASA rightly leave nothing to chance.

The crew of STS-125 is comprised seven astronauts, Commander Scott "Scooter" Altman for whom STS-125 would be his fourth spaceflight and his second visit to Hubble; Pilot Gregory Johnson making his first spaceflight; mission specialist Michael Good a first time flyer; Megan McArthur the flight engineer and lead robotics specialist, making her first space flight; John Grunsfeld, a NASA veteran, who would be making his fifth flight into space and his third visit to Hubble; Mike Massimino, making his second flight into space and second to Hubble; and finally Andrew Feustal another first time flyer.

One thing that made the crew seem more tightly knit was the fact that they had been in training for this mission for years, each subsequent delay brought them closer together as a groups and in turn gave them more time to practice the tasks they would face in the coming days of the mission.

Whilst en-route the crew passed the VAB in order to drop off Chief Astronaut Steve Lindsay so he could go out to the Shuttle Landing Facility (SLF) and fly weather recon. The prime crew then continued their trip out to Pad 39A and their entry into the vehicle ready for launch. As for me, it was back into the press bus and back to the press site to soak up more of the atmosphere prior to launch, not long to go now, just a few hours. I watched the crew ingress Atlantis on the monitors in the press room and then decided to take a walk to set up my camera. Many more people were doing the same thing, professional photographers were setting their gear up with remote triggers which they could just leave in-situ and not have to worry about it at launch once they and I were set.

T minus 2 minutes, the anticipation starts to build, then were down to T-30, 20 , 10 and I just stand in awe this is, after all my first launch..

Main engine ignition, booster ignition and at 2:01pm EDT Atlantis was on her way. I am struck by the sheer intensity of the brightness, truly amazing and then I am aware of the people whooping and waving as Atlantis rose into the clear sky. A few seconds later I felt it; the vibration of the air caused by the SRB's as it pounded my chest and crackled in my ears, a sensation that will stay with me always, truly incredible. A Shuttle launch is not just a visual thing; it is a whole body experience. Go Atlantis! Later, I was informed that this had been a particularly noisy launch due to the higher than normal temperatures, so much so in fact that one of the light fittings in the press room had been dislodged from the ceiling.

Outside I watched as Atlantis soared into the sky through some light cloud, I could still see the glow of the SRBs almost up to SRB separation. Atlantis was on her way to orbit. I meanwhile headed back to the press room and attended the post launch press conference.

We found out that soon after launch and during the initial phase of the ascent it was reported that a problem was happening with a hydrogen tank transducer and a circuit breaker. Flight controllers alerted the crew immediately but advised them to disregard the associated alarms and continue their flight to orbit.

After working through their post launch checklists, the crew opened the payload bay doors, deployed the microwave Ku Band antenna used for communicating via the Tracking and Data Relay Satellite TDRS. They then moved through their checklist into the robotic activities portion of the day including payload bay and crew cabin surveys.

Catching Hubble and first EVA

On the third day of the mission the crew performed the Hubble rendezvous operations that included burning the orbiter's engines to refine the approach to the Hubble telescope. The crew had been having problems with communications and as a result it caused some delays in getting towards the telescope. The crew guided Atlantis to within fifty feet of the telescope and 20 minutes late Megan McArthur successfully grappled Hubble 340 miles above Western Australia. Just under an hour later the telescope was safely soft docked in the payload bay.

Hubble was once again "captured". Further along in the day 3 schedule, four of the crew, Grunsfeld and Feustel along with Michael Good and Mike Massimino set work on preparing for the next day's EVA,

John Grunsfeld and Andrew Feustel, perched alone on the end of the Atlantis' RMS arm, conduct the first of five STS-125 spacewalks to repair and upgrade the Hubble Space Telescope, temporarily locked down in the cargo bay of the Earth-orbiting shuttle. Credit: NASA

While standing on the end of Atlantis' RMS arm, STS-125 mission specialist Michael Good works on the Hubble Space Telescope. Good and fellow mission specialist Mike Massimino (out of frame) continue work on the HST, locked down in the orbiter's cargo bay. Credit: NASA

they set about gathering the tools needed that had been developed by aerospace and defence company ATK and then they checked out the suits and equipment that would be used during the EVA.

The crew was informed that the damage assessment team had cleared all of the orbiter's TPS tiles and blankets, and that all looked safe which meant that the crew was no longer required to do a detailed tile inspection. Incidentally data actually showed there had been a wing impact event on launch as it had been on Columbia in 2003 but it was deemed to be well below the force that would indicate a flight issue.

It was noted too that when a camera inspection of Atlantis's cargo bay had been carried out it seemed that there was some sort of dust or debris around the box housing the Wide Field Camera (WFC-3). The crew took hi resolution images of the debris and it as deduced that it was not present at launch but most likely it was caused by something that vibrated and shook loose from the payload bay insulation blankets during launch 3 days prior. The crew were advised where at all possible to be careful when working around the WFC-3 container but that is wasn't a major issue.

On the fourth day of the flight the crew awoke to the song Stick Shifts and Safety belts by CAKE an American Indie band from Sacramento, California played for Andrew Feustal.

Today was going to see the first EVA and it was John Grunsfeld and Andrew Feustal that were given the honour.

Using a high resolution camera Feustel provided the team on the ground a visual inspection report on the material seen around the WFC-3 box, reporting to the ground team that "I don't really see any of those particles" After getting their tools and equipment for the EVA in place and set they began to remove the old Wide Field Planetary Camera 2 (WFPC-2), which was way back in 1993 during the the STS-61 Mission, Grunsfeld and Feustel replaced it with the new camera but not without incident as Feustel initially had some problems removing one of the bolts

from the old camera which needed more torque than they thought would be required.

Feustel achieved the torque required with the aid of a torque limiter that fortunately had been thought of and stored back in the airlock. The great worry was that the bolt holding the WFPC-2 would sheer and break thus not allowing it to be removed, that would have been disastrous, but the ground team gave Feustel the go ahead to apply as much force as he thought it would take and to everyone's relief in came out, job done!

Once they had installed the new WFC-3, which will allow Hubble to see farther into space and across a wider spectrum of colours, they connected it up to power, teams at Goddard Space Flight Centre sent commands to the unit to see if it was "alive and awake", fortunately it was, and that indicated that the EVA team had installed it correctly, task 1 had been completed.

Back in September 2008 when the STS-125 mission was being prepared for launch, one of the computers on Hubble failed. This was the Science Instrument Command and Data Handling Unit, or SIC&DH that's used to send data to Hubble's instruments and then formats it ready for transmission to the ground. This was replaced and the final EVA task for day four got under way, installation of what is termed the Soft-Capture Mechanism (SCM).

Second and third EVAs

Good news on day 5, the ground crew informed the crew that the WFC-3 had passed all the overnight tests, indicating that it was in good working order, a great result for EVA 1.

Now though it was the turn of Massimino and Good.

The first task for EVA 2 was the removal and replacing Hubble's three gyroscope rate sensing units (RSUs). Each unit contains two gyroscopes that allow the telescope to point itself. The first unit was replaced without any issues but when they attempted to replace the second unit, RSU 3, the unit would not align onto the guide pins, and they could not get it to sit correctly into the vacated bay, so ground managers had to come up with a solution. It was duly decided that the best way forward would be to put the RSU unit originally intended for the number one bay into the 3rd bay, fortunately that worked, but he problems were not over yet, after attempting to install the second unit into the third and last bay this one would not now seat correctly in place and in the end they gave up trying.

It was then decided to use one unit that was carried as an additional fight spare. This one was originally removed during STS-103 and had been taken back to Earth and refurbished, not ideal but at least it worked. This was a critical series of installations tasks for the mission critical to Hubble's survival in orbit. Three sets of gyros had already failed to work in the past so replacement was essential for the longevity of the telescope.

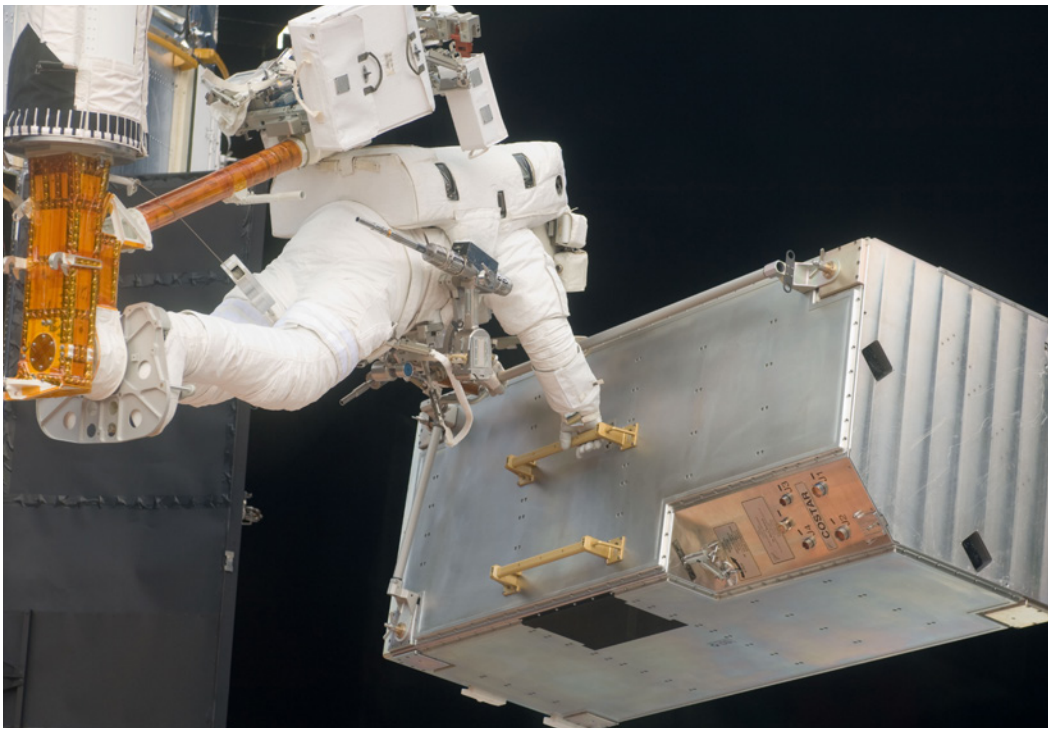
Massimino and Good them moved on to the batteries and replaced them too, a good day all in all.

Today the crew awoke to the sound of a song called Hotel Ceppolina by Fuzzbox Piranha played especially for Hubble veteran John Grunsfeld but once everyone was up it was down to the serious business of EVA number 3.

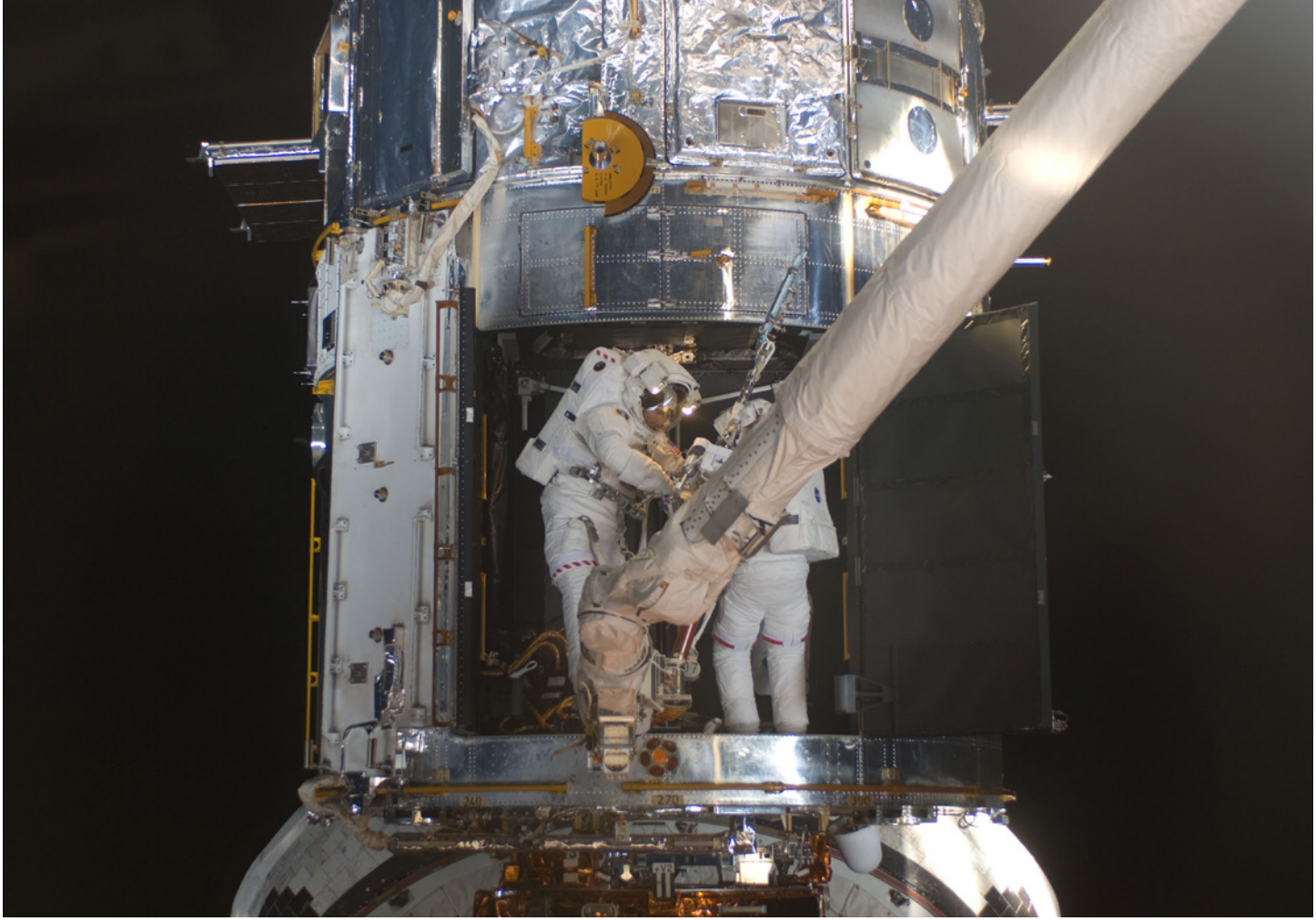
Today's tasks for John Grunsfeld and Andrew Feustel started with one that was deemed to be one of the most challenging of the mission and certainly one of the most uncertain in terms of it going to plan and working, but these task were considered to be very important, some of the most important of the entire STS-125 mission.

The first job was to remove the now unused Corrective Space Telescope Axial Replacement (COSTAR), this as you will recall was the set of mirrors that corrected Hubble's visions after the near disastrous problem with Hubble's primary mirror. The task was to remove this and replace it with the brand new Cosmic Origin Spectrograph (COS). The COS is designed to study the large scale structure in the universe and how galaxies, stars, and planets evolved into what we see today.

The next task would be to try to repair the Advance Camera For Surveys, (ACS). The ACS had been a problem for some time, it was installed in Hubble on servicing Mission 3B in 2002 but an electronics failure in 2007 rendered useless the most useful two science channels, now just



Andrew Feustel, positioned on a foot restraint on the end of Atlantis' remote manipulator system (RMS), moves the Corrective Optics Space Telescope Axial Replacement (COSTAR) during the mission's third EVA session to refurbish and upgrade the Hubble Space Telescope. Credit: NASA



Astronauts Michael Good (left) and Mike Massimino, both STS-125 mission specialists, participate in the mission's fourth session of extravehicular activity (EVA) as work continues to refurbish and upgrade the Hubble Space Telescope. During the eight-hour, two-minute spacewalk, Massimino and Good continued repairs and improvements to the Space Telescope Imaging Spectrograph (STIS) that will extend the Hubble's life. Credit: NASA

operating on one remaining channel a repair attempt on this EVA would try to reinstate the Wide Field Channel. It was this channel that was responsible for 70% of the pre 2007 ACS Science and importantly it is hoped that once repaired it could answer some of the questions relating to the mysterious origins of Dark Matter and Dark Energy. With the ACS Wide Field Camera 3 (WFC-3) combined they would form a formidable team of instruments in the pursuit of those answers. The problem however for the ACS was that it never had been designed to be repaired in space!

Using the specially designed tools from ATK, the spacewalkers carefully removed panels in the unit for access and slowly and methodically replaced the camera's electronic circuit boards and power supply. After a ground check the ACS seemed to working OK and the repair deemed a success even though one channel wasn't operating optimally. It was amazing that ground controllers envisaged EVA 3 to be the trickiest of them all with foreseen issues but it turned out to be the smoothest EVA of the mission so far. Well done Grunsfeld and Feustel.

Fourth and fifth EVAs

Alternating the EVA crew again on day 7 saw the return of Mike Massimino and Michael Good. Number one task today was the ambitious repair of the Space Telescope Imaging Spectrograph (STIS). This instrument was installed in Hubble during servicing mission 2 in 1997.

Unfortunately, the instrument stopped functioning in August of 2004 due to a power supply failure and had been in "Safe Mode" since that time. A highly versatile instrument STIS mainly used for spectroscopy the splitting of light into it's component wavelengths in order to give us a better understanding about Chemical and temperature of Comets, stars, interstellar gas and galaxies so it was high up on the list of things to get working again.

However, the repair was not going to be an easy one. Massimino would have to remove 111 screws in order to remove the plate that allows access to the power supply. Anyone who has done any DIY on earth will know how fiddly it can be removing screws and how easy it is to loose them, imagine trying this in orbit wearing bulky gloves; it gives an idea of how hard a task it was.

The task was made all the more difficult because Massimino had encountered a problem with one of the Hubble handrails. It had a stripped a bolt and this prevented it from coming loose so they could fit the plate. It was decided that the only real way of removing the handrail would be for Massimino to use force and literally break it free. This wasn't without risk either as it could not only damage the skin of the telescope it could release dangerous debris into the telescope and into space and it could have had such sharp edges that if it wasn't handled safely it may well have cut into Massimino's

Astronauts John Grunsfeld (left) and Andrew Feustel, both STS-125 mission specialists, participate in the mission's fifth and final ever session of extravehicular activity (EVA) to repair and upgrade the Hubble Space Telescope. During the seven-hour and two-minute spacewalk, Grunsfeld and Feustel installed a battery group replacement, removed and replaced a Fine Guidance Sensor and three thermal blankets (NOBL) protecting Hubble's electronics. Credit: NASA

space suit. Fortunately he managed to break and remove it safely some three hours into the EVA.

As it turned out, the fastener-capture plate that had been so cleverly designed on the ground proved to be of great use and the screws were removed ok now access had been gained. Another issue then occurred when power to one of Massimino's tools failed and a spare had to be retrieved. Whilst doing this Massimino took time to re charge his suits Oxygen supply.

This issue had taken up valuable EVA time and by now the two space walkers were behind schedule so ground controllers decided that the task of replacing old thermal blankets with the New Outer Blanket Layers (NOBL) onto Bay 8 should be postponed and moved into another EVA period.

It was by now Day 8 of Atlantis's scheduled 11-day mission and the EVA 5 was slated to be the last. It fell to Grunsfeld and Feustel so finish up any last chores.

Firstly they swapped out the battery module from Bay 3 and then replaced it with a second battery. They also did the task of replacing the Fine Guidance Sensor 3 on the telescope. Hubble has three of these sensors which help it to point itself. Two of the sensors are used to point the telescope and then lock it onto any astronomical target and the third sensor is then used to take positional measurements known as astrometry. All three are essential for Hubble.

Because Grunsfeld and Feustel had completed these tasks ahead of schedule they were able to replace three sets of the NOBLs including the ones that Massimino and Good had run out of time to replace on EVA 4.

All that remained were the four months of checking out and calibrating the instruments before scientific observations could begin again. Hubble was alive again!

Releasing Hubble

Day 9 was slated to be the day that the crew of Atlantis would release Mr. Hubble's telescope back into orbit and bid farewell. Megan McArthur captured Hubble once more with the robotic arm and slowly, carefully, methodically began the process of extracting Hubble from the payload bay and back into Earth's orbit.

Ground teams worked through several check lists and finally the command came for Megan to release Hubble back into space. Pilot Gregory Johnson performed a small engine burn and slowly Atlantis moved away from the telescope. STS-125's mission to Hubble was finished.

And it was with that the STS-125 Commander Altman commented "Hubble has been released, it's safely back on its journey of exploration as we begin steps to conclude ours" he concluded with "And now Hubble can continue on its own, exploring the cosmos, and bringing it home to us as we head for home in a few days. Thank you"

An explosive quartet

Supernova 'multiplied' by galaxy

Whilst looking closely at a massive elliptical galaxy and its associated galaxy cluster MACS J1149+2223 — whose light took over 5 billion years to reach us — astronomers have spotted a strange and rare sight. The huge mass of the galaxy and the cluster is bending the light from a much more distant supernova behind them and creating four separate images of it. The light has been magnified and distorted due to gravitational lensing and as a result the images are arranged around the elliptical galaxy in a formation known as an Einstein cross.

Although astronomers have discovered dozens of multiply imaged galaxies and quasars, they have never before seen multiple images of a stellar explosion.

Astronomers using the Hubble Space Telescope have, for the first time, spotted four images of a distant exploding star. The images are arranged in a cross-shaped pattern by the powerful gravity of a foreground galaxy embedded in a massive cluster of galaxies. A close-up of the Einstein cross is shown in the inset. Credit: NASA, ESA, S. Rodney (John Hopkins University, USA) and the FrontierSN team; T. Treu (University of California Los Angeles, USA), P. Kelly (University of California Berkeley, USA) and the GLASS team; J. Lotz (STScI) and the Frontier Fields team; M. Postman (STScI) and the CLASH team; and Z. Levay (STScI)

"It really threw me for a loop when I spotted the four images surrounding the galaxy — it was a complete surprise," said Patrick Kelly of the University of California Berkeley, USA, a member of the Grism Lens Amplified Survey from Space (GLASS) collaboration and lead author on the supernova discovery paper. He discovered the supernova during a routine search of the GLASS team's data, finding what the GLASS group and the Frontier Fields Supernova team have been searching for since 2013. The teams are now working together to analyse the images of the supernova, whose light took over 9 billion years to reach us.

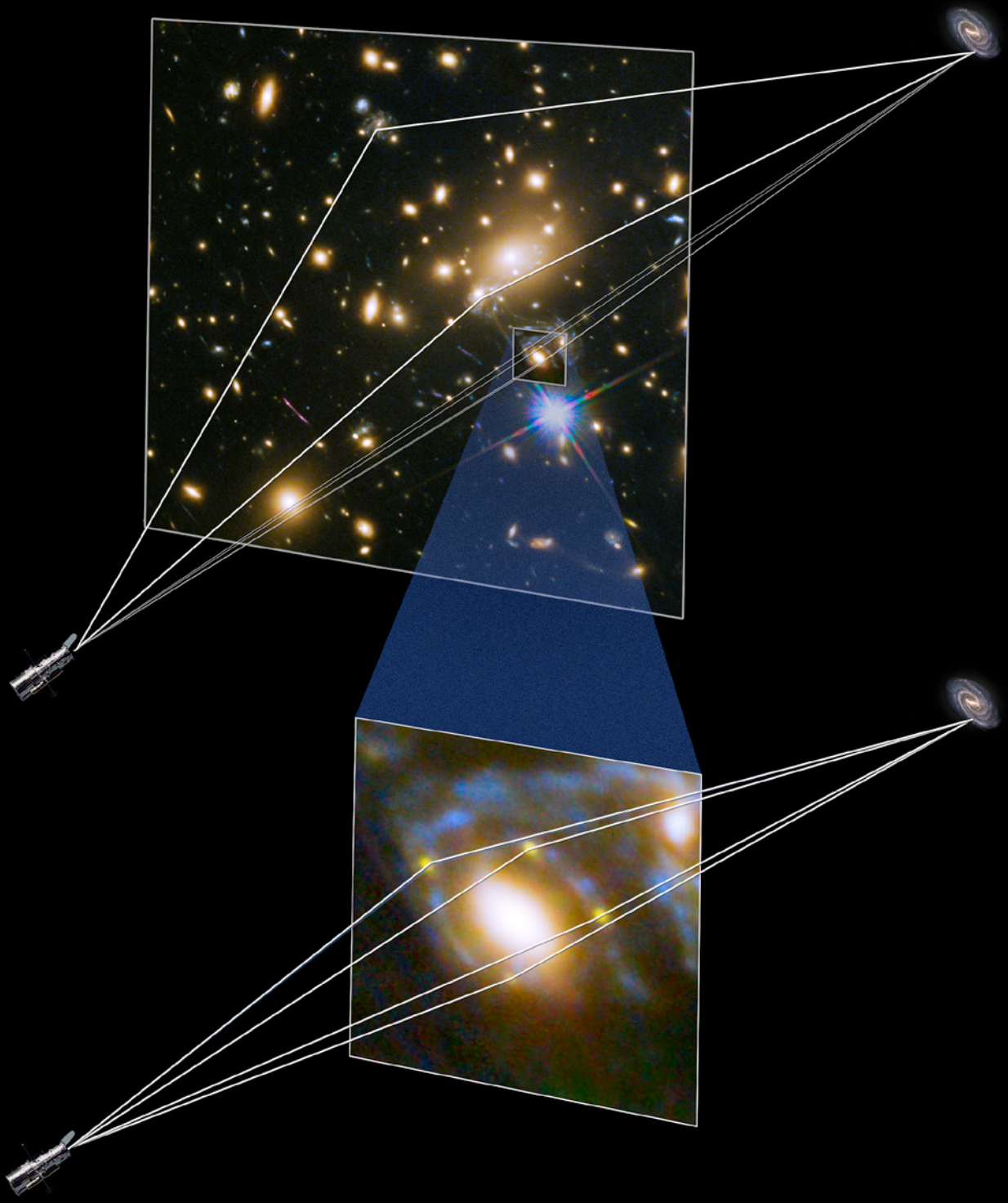
"The supernova appears about 20 times brighter than its natural brightness," explains the paper's co-author Jens Hjorth from the Dark Cosmology Centre, Denmark. "This is due to the combined effects of two overlapping lenses. The massive galaxy cluster focuses the supernova light along at least three separate paths, and then when one of those light paths happens to be precisely aligned with a single elliptical galaxy within the cluster, a secondary lensing effect occurs." The dark matter associated with the elliptical galaxy bends and refocuses the light into four more paths, generating the rare Einstein cross pattern the team observed.

This unique observation will help astronomers refine their estimates of the amount and distribution of dark matter in the lensing galaxy and cluster. There is more dark matter in the Universe than visible matter, but it is extremely elusive and is only known to exist via its gravitational effects on the visible Universe, so the lensing effects of a galaxy or galaxy cluster are a big clue to the amount of dark matter it contains.

When the four supernova images fade away as the explosion dies down, astronomers will have a rare chance to catch a rerun of the explosion. The supernova images do not arrive at the Earth at the same time because, for each image produced, the light takes a different route. Each route has a different layout of matter — both dark and visible — along its path. this causes bends in the road, and so for some routes the light takes longer to reach us than for others. Astronomers can use their model of how much dark matter is in the cluster, and where it is, to predict when the next image will appear as well as using the time delays they observe to make the mass models even more accurate.

"The four supernova images captured by Hubble appeared within a few days or weeks of each other and we found them after they had appeared," explains Steve Rodney of Johns Hopkins University, USA, leader of the Frontier Fields Supernova team. "But we think the supernova may have appeared in a single image some 20 years ago elsewhere in the cluster field, and, even more excitingly, it is expected to reappear once more in the next one to five years — and at that time we hope to catch it in action."

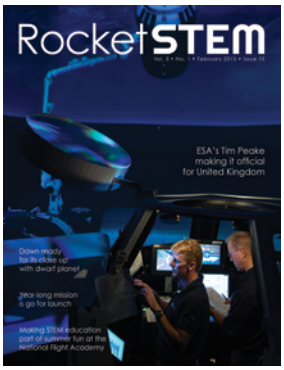
The supernova has been nicknamed Refsdal in honor of Norwegian astronomer Sjur Refsdal, who, in 1964, first proposed using time-delayed images from a lensed supernova to study the expansion of the Universe. "Astronomers have been looking to find one ever since," said Tommaso Treu of the University of California Los Angeles, USA, the GLASS project's principal investigator. "And now the long wait is over!"



This illustration shows how four different images of the same supernova were created when its light was distorted and magnified by the huge galaxy cluster MACS J1149+2223 in front of it.

The light has been magnified and distorted due to gravitational lensing and as a result the images are arranged around the elliptical galaxy in a formation known as an Einstein cross.

The massive galaxy cluster focuses the supernova light along at least three separate paths, and then when one of those light paths happens to be precisely aligned with a single elliptical galaxy within the cluster, a secondary lensing effect occurs. The dark matter associated with the elliptical galaxy bends and refocuses the light into four more paths, generating the rare Einstein cross pattern that the team observed. *Credit: NASA & ESA*



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